This is a digital copy of a book that was preserved for generations on library shelves before it was carefully scanned by Google as part of a project to make the world's books discoverable online.

It has survived long enough for the copyright to expire and the book to enter the public domain. A public domain book is one that was never subject to copyright or whose legal copyright term has expired. Whether a book is in the public domain may vary country to country. Public domain books are our gateways to the past, representing a wealth of history, culture and knowledge that's often difficult to discover.

Marks, notations and other marginalia present in the original volume will appear in this file - a reminder of this book's long journey from the publisher to a library and finally to you.

Usage guidelines

Google is proud to partner with libraries to digitize public domain materials and make them widely accessible. Public domain books belong to the public and we are merely their custodians. Nevertheless, this work is expensive, so in order to keep providing this resource, we have taken steps to prevent abuse by commercial parties, including placing technical restrictions on automated querying.

We also ask that you:

+ *Make non-commercial use of the files* We designed Google Book Search for use by individuals, and we request that you use these files for personal, non-commercial purposes.

+ *Refrain from automated querying* Do not send automated queries of any sort to Google's system: If you are conducting research on machine translation, optical character recognition or other areas where access to a large amount of text is helpful, please contact us. We encourage the use of public domain materials for these purposes and may be able to help.

+ *Maintain attribution* The Google "watermark" you see on each file is essential for informing people about this project and helping them find additional materials through Google Book Search. Please do not remove it.

+ *Keep it legal* Whatever your use, remember that you are responsible for ensuring that what you are doing is legal. Do not assume that just because we believe a book is in the public domain for users in the United States, that the work is also in the public domain for users in other countries. Whether a book is still in copyright varies from country to country, and we can't offer guidance on whether any specific use of any specific book is allowed. Please do not assume that a book's appearance in Google Book Search means it can be used in any manner anywhere in the world. Copyright infringement liability can be quite severe.

About Google Book Search

Google's mission is to organize the world's information and to make it universally accessible and useful. Google Book Search helps readers discover the world's books while helping authors and publishers reach new audiences. You can search through the full text of this book on the web at `http://books.google.com/`

Stanford University Libraries

STANFORD UNIVERSITY LIBRARIES

BRANNER
GEOLOGICAL LIBRARY

STANFORD UNIVERSITY LIBRARIES

SITY LIBRARIES · STANFORD UNIVERSITY LIBRARI
UNIVERSITY LIBRARIES · STANFORD UNIVERSITY LIB
Y LIBRARIES · STANFORD UNIVERSITY LIBRARIES · S
STANFORD UNIVERSITY LIBRARIES · STANFORD UN
ES · STANFORD UNIVERSITY LIBRARIES · STANFO
ORD UNIVERSITY LIBRARIES · STANFORD UNIVERS
SITY LIBRARIES · STANFORD UNIVERSITY LIBRARI
UNIVERSITY LIBRARIES · STANFORD UNIVERSITY LIB
Y LIBRARIES · STANFORD UNIVERSITY LIBRARIES · S
· STANFORD UNIVERSITY LIBRARIES · STANFORD UN
ES · STANFORD UNIVERSITY LIBRARIES · STANFO
ORD UNIVERSITY LIBRARIES · STANFORD UNIVERS
SITY LIBRARIES · STANFORD UNIVERSITY LIBRAR

No. 325 Series { E, Chemistry and Physics, 53
Q, Fuels, 5 }

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, DIRECTOR

A STUDY OF
JR HUNDRED STEAMING TESTS

MADE AT THE FUEL-TESTING PLANT, ST. LOUIS, MO. IN 1904, 1905, AND 1906.

BY

LESTER P. BRECKENRIDGE

WASHINGTON
GOVERNMENT PRINTING OFFICE
1907

CONTENTS.

	Page.
ı. P. Breckenridge	7
by Walter T. Ray	9
est data	11
ombustion	11
. rate of heat evolution	13
on-chamber temperature	18
E. code boiler efficiency (72*)	26
in coal	32
clinker	32
liameter of coal	45
of rated capacity developed	51
y	52
	56
nd coal	58
ıtile matter,” “fixed carbon,” “water of composition,” and ustible”	58
l combustion space	59
of combustion at various points along the flame	60
on-chamber baffle wall	62
on-chamber temperature	63
to explain unaccounted-for loss in heat balance	64
of nitrogen in flue gases to efficiency 72* and to size of coal, and :ent of CO to efficiency 72*	64
of CO_2 in flue gases to per cent of completeness of combustion	65
of differences of draft to pounds of dry chimney gases per pound nbustible”	66
of coals	68
ydrogen ratio in air-dried coal	68
ydrogen ratio in coal as received	70
ydrogen ratio in dry coal	77
ydrogen ratio in coal as fired as affecting efficiency 72*	82
of ratio of carbon to available hydrogen and of per cent of avail- 'drogen to efficiency 72*	83
ıydrogen to available hydrogen	85
of “volatile matter” in the “combustible”	89
·bon (proximate analysis)	90
of efficiency 72* to per cent of oxygen in “combustible”	92
ıermal units per pound of dry coal	93
ısh to sulphur in dry coal	94

Page.
Suggested steam-turbine cycles, heat absorption, and boiler efficiencies.... 95
The boiler and the furnace and their efficiencies.... 95
High initial furnace temperature and its effect on economy.... 100
Low steam pressure and its effect on economy.... 102
Heat transmission through boiler tubes, and true boiler and furnace efficiencies.... 105
Theoretical considerations.... 109
True boiler efficiencies dependent only on physical size, shape, and arrangement of boiler.... 112
Influence of velocity of gases on heat absorption.... 113
Practical application of theory of heat absorption to a fire-tube boiler.... 118
Water circulation as affecting heat absorption.... 120
Calculation of heat absorption along a fire tube.... 121
Higher initial temperature means higher final temperature when heat absorption is by convection only.... 124
Modifying factors of the theory of heat transmission.... 125
Temperature test of Perry's equation.... 132
Ratio modified in practice by initial temperature.... 134
A conception of boiler and furnace efficiency.... 137
The code form and a revised form of heat balance.... 137
Derivation of the constant-capacity curves of fig. 65.... 141
Derivation of boiler efficiency (E_5).... 142
Derivation of true boiler efficiency (E_4).... 143
Method of estimating radiation.... 143
Plotting of probability curves.... 146
Miscellaneous.... 149
Reliability of observation and data.... 149
Computations of a steaming test.... 151
Dissociation curves of carbon dioxide and water vapor.... 153
Water-jacketed gas sampler.... 154
Comparison of readings of certain gas samplers.... 155
Flue-gas sampler.... 156
Unaccounted-for percentages probably too high.... 156
Probability curves.... 158
Relation of temperature of products of combustion to pounds of air used.. 159
Circulation indicator.... 160
C-shaped v. flat-bottomed tube tiles.... 164
Orsat totals.... 164
Per cent of CO in combustion chamber.... 166
Pounds of dry chimney gas per pound of "combustible".... 167
Effect of direction, velocity, relative humidity, and temperature of wind on efficiency 72*.... 167
Relation of unaccounted-for loss to ash passing over bridge wall.... 168
The law of mass action.... 170
Dimensions of boilers and settings.... 173
True boiler efficiency.... 174
General conclusions.... 174
Commercial considerations.... 177
Bibliography.... 179
Glossary.... 180
Index.... 185

ILLUSTRATIONS.

Page.

1. Relations of rate of combustion to three stated factors.................. 12
2. Relations of rate of combustion to three stated factors taken from heat balance.. 12
3. Relations of rate of heat evolution to three stated factors.............. 13
4. Relations of rate of heat evolution to four stated factors.............. 13
5. Relations of rate of heat evolution to two stated factors.............. 14
6. Theoretical curves of factors affecting heat absorption.................. 15
7. Velocity of water circulation in boiler as affected by rate of steaming... 16
8. Relations of coal burned to rated capacity and to efficiency 72*....... 17
9. Variation of temperature with firing in Heine furnace.................. 18
10. Wanner optical pyrometer in position for standardizing................ 19
11. Combustion-chamber temperature as a function of two stated factors... 20
12. Relations of combustion-chamber temperature to three stated factors.. 21
13. Relation of flue-gas composition to combustion-chamber temperature.. 22
14. Relation of gas composition to temperature in rear of combustion chamber.. 23
15. Water-jacketed gas sampler.. 24
16. Relation of combustion-chamber temperature to flue-gas temperature.. 24
17. Relations of combustion-chamber temperature to three stated factors... 25
18. Relations of efficiency 72* to CO and CO_2, and of CO_2 to efficiency 72*.. 27
19. Relations of nitrogen to efficiency 72* and to size of coal, and of CO to efficiency 72*.. 28
20. Theoretical curves of heat absorption as affected by air supply.......... 29
21. Classifications on bases of efficiency 72* and of clinker................ 30
22. Relation of moisture in coal to efficiency 72*, and of efficiency 72* to ash. 33
23. Relation between ratio of iron in coal to ash in coal and boiler efficiency 72*.. 35
24. Relations of clinker in refuse to four stated factors.................... 36
25. Coal classification based on carbon-hydrogen ratio in dry coal.......... 37
26. Relation of per cent of ash in dry coal to efficiency 73................ 40
27. Relations of per cent of ash to seven stated factors.................... 41
28. Relations of sulphur in coal to four stated factors...................... 43
29. Relations of size of coal to eight stated factors........................ 46
30. Relations of size of coal to seven stated factors........................ 48
31. Relation of CO_2 in flue gases to completeness of combustion............ 51
32. Comparison of pyrometer and water-jacket temperatures in combustion chamber.. 55
33. Smoke classification on basis of black smoke as 100 per cent........... 56
34. Gas-mixing wall built in the Heine safety water-tube boiler........... 62
35. Relations of combustion-chamber temperature to three stated heat-balance factors.. 63

Page.
Fig. 36. Relations of differences of draft to pounds of dry chimney gases per pound of "combustible" 66
37. Coal classification based on carbon-hydrogen ratio from analysis of air-dried samples 69
38. Coal classification based on carbon-hydrogen ratio 71
39. Coal classification, Group K 74
40. Coal classification, Group M 75
41. Coal classification, Group O 76
42. Coal classification, Group A 79
43. Coal classification, Group B 80
44. Coal classification, Group D 81
45. Coal classification, Group Y 82
46. Efficiency curves of coal classified according to the per cent of rating 83
47. Classification of tests based on available hydrogen 84
48. Relation between the ratio of volatile carbon to total carbon and efficiency 72* 86
49. Coal classification based on ratio of hydrogen to available hydrogen 87
50. Relations of "volatile matter" in the "combustible" to two stated factors 89
51. Relations of "fixed carbon" to six stated factors 91
52. Relations of efficiency 72* to per cent oxygen in "combustible" 92
53. Relations of B. t. u. value of coal to five stated factors 93
54. Temperature-entropy diagrams for boiler 96
55. Availability to a boiler of heat of combustion of carbon 102
56. Temperature-entropy diagrams for steam-turbine cycles 105
57. Diagram illustrating the theory of the dislodgment of adhering gaseous molecules 110
58. Relative B. t. u. absorbed at different points in a boiler tube 123
59. Relative temperatures of the products of combustion passing through a boiler tube 125
60. Diagrams illustrating temperature gradients of moving gases 127
61. Relations of pounds of gas to heat transmitted and of heat radiation to actual temperature 131
62. Classification based on ratio of certain stated temperatures 133
63. Relation of ratio of certain stated temperatures to rated capacity 136
64. Relation of boiler efficiency to unaccounted-for heat; availability of heat to boiler 138
65. Curves of constant boiler efficiency (E_5) and of constant capacity developed 141
66. Curves of constant true boiler efficiency (E_4) and of constant capacity developed 144
67. Probability curves (approximate) 147
68. Relation of unaccounted-for loss to CO loss 151
69. Dissociation curves of water vapor and carbon dioxide 154
70. Comparison of readings of multitubular gas sampler and of single tube in stack 155
71. Flue-gas sampler installed to replace A. S. M. E. multitubular sampler 157
72. Diagram illustrating probability curve 158
73. Theoretical curves showing relation of temperature to pounds of air used 160
74. Circulation indicator mounted in boiler 161
75. Result of observations with circulation counter 162
76. Dimensions and details of boiler setting 174

PREFACE.

The fuel tests discussed in this paper were made under two Heine water-tube boilers by the boiler division of the United States Geological Survey fuel-testing plant at St. Louis, Mo. These tests began during the Louisiana Purchase Exposition, in 1903, and have been in progress since that time. The coals tested have been collected from all the prominent fields of the United States.

It has been the object to compare fuels by determining the evaporative performance of the boilers when using the various coals. Careful and complete observations have been made with each coal, so that it should be possible for engineers to determine from an examination of the records whether the conditions of the tests were favorable or unfavorable for the character of the coals tested.

The results of tests by the several divisions of the fuel-testing plant that have been published thus far appear in (*a*) Bulletins Nos. 261 and 290 of the United States Geological Survey, giving preliminary reports of the operations of the plant; (*b*) Professional Paper No. 48 of the Survey, giving complete and detailed information of the tests made during the Exposition.

The steaming tests were in charge of D. T. Randall during the Exposition period and of Walter T. Ray since that time. These men have been ably assisted by a corps of trained observers and computers, who have been alert, patient, and painstaking.

As soon as a considerable number of tests were available, it seemed desirable to begin a comparison of the various tests on the basis of such usual factors as over-all efficiency, rate of combustion, temperature of escaping gases, evaporation per square foot of heating surface, etc. It soon developed that many interesting and apparently valuable results were brought out by these comparisons, and hence they were extended. The discussions of facts led to a search for theories, and the men of the division sought out available literature bearing on the various subjects under discussion. Thus has accumulated the material here presented. It is not the work of any one, but of all.

To Messrs. Walter T. Ray, Henry Kreisinger, and Harry W. Weeks should be accorded especial credit for preparing the larger part of this material. Except for the cooperation and careful work of the chemical division, under the supervision of Dr. N. W. Lord, much of the work here reported would not have been possible.

Many of the relations submitted have been worked out at the suggestion of different engineers who were interested in particular phases of the work. Some repetition in the matter presented is perhaps unavoidable on account of the nature of the subject. Possibly much that is new has developed during the discussion, because never before have 400 boiler tests been made under two boilers (exactly alike) with coals and lignites from all sections of the United States and with all tests fired by the same expert fireman.

Acknowledgment is gratefully made to the many engineers of the country for helpful suggestions and kind criticisms that have come to me while endeavoring to direct the tests of this division so that they would prove of the greatest value to the industries of the nation, and to those engineers whose problem is still to furnish boilers of greater capacity and furnaces of higher economy. It must not be forgotten that all discussion is based on the results obtained in a single furnace with one type of boiler, but many of the results should have wide application in any furnace and under any type of boiler. Helpful suggestions or criticisms from manufacturers or engineers are again invited.

In submitting this paper I desire to thank Dr. Joseph A. Holmes, expert in charge of the fuel-testing plant, for his uniformly courteous consideration of the plans and needs of the boiler division and for the freedom which he has always allowed us in carrying on the work. We have appreciated his confidence and can only hope that it has been merited.

L. P. BRECKENRIDGE,
Engineer in Charge of the Boiler Division.

URBANA, ILL., *January 14, 1907.*

A STUDY OF FOUR HUNDRED STEAMING TESTS.

By Lester P. Breckenridge.

INTRODUCTION.

By Walter T. Ray.

Origin of the bulletin.—As the so-called "boiler tests," made by the fuel-testing plant at St. Louis, gradually accumulated, it became evident to the men making them that a great deal of incidental work was assuming the shape of a considerable compilation of plottings and calculations of various matters pertaining to the tests, and that certain details of the work were beginning to shed light on the inner reasons for the unreliability of tests of coals made under steam boilers. Much research work was being done in the boiler room simultaneously with the steaming tests proper, and of this work also certain details shed light on the same unreliabilities.

It was originally intended to insert these results in the regular bulletins of the fuel-testing plant, but the further the work went the less of a basis for general conclusions it seemed to be. For this reason publication was postponed until a large amount of matter was on hand. In order to avoid undue bulk, no account of most of the work itself is given. Many of the negative results obtained are presented, however, on the general principle that negative results are usually worth as much as positive results.

Scope of the work.—An especially striking instance of the value of negative results was noted in an attempt to check up the readings of an optical pyrometer used on the combustion chamber by calculating the initial temperatures of the gases entering the boiler in each test, so as to find whether the pyrometer read too high or too low when sighted on flame. The basis used for the calculation was the efficiency noted as "72*, efficiency of boiler, per cent" in the code of the American Society of Mechanical Engineers. The calculated temperatures of combustion were ridiculous, and were very puzzling for some weeks. Meanwhile a study was made of some chapters in John Perry's book, "The Steam Engine and Gas and Oil Engines," relating to the manner in which fluids give up heat and momentum, and making application of these principles to steam boilers. A development of these ideas and their application to the apparatus used in these tests constitutes what is believed to be the most valuable part of this bulletin. It is thought that a fairly trustworthy separation has been effected for most tests of the true boiler efficiency and the percentage of completeness of combustion. Apparently the former is constant, as the theory indicates, and the "practical" boiler efficiency differs from it by only a very few per cent, the main cause of the difference apparently being that as a rule all of the fuel is not burned.

All of this work has been done with the hope of discovering new guiding principles for use in forecasting the results of burning any given fuel more accurately than can now be done from chemical analyses and observation of physical characteristics. It is true that at present the choice of coals in any market for any given use can be narrowed down to perhaps 20 per cent of the coals considered by a consideration of market price, freight charges, chemical analysis, heating value, and physical characteristics; but the ambition of the boiler division is to work toward that completeness of knowledege whereby about three-fourths of the 20 per cent can also be discarded after laboratory investigations.

It is also the intention of the boiler division to study the principles of fuel combustion to such advantage that much coal can be saved, and that cheap fuels can be used in certain operations where higher-priced ones are now considered necessary. Such savings will really redound to the benefit of producers of the best fuels of all grades quite as much as to the benefit of consumers. A number of new lines of work are suggested in the text; several of these it is planned to take up soon, and some of them may give data for determining the burning qualities of fuels independently of the apparatus in which the process takes place.

Perhaps the most important reason for doing the research work, and for making so many comparisons of the data obtained from all tests, was the feeling that the testing of fuels under boilers is at best only approximately comparative. In short, it was the feeling that we were on the wrong track, without knowing of a better one, which led us to do the research work.

This work was performed and the results were prepared for publication under the direction of Prof. L. P. Breckenridge, engineer in charge of the boiler division, by the following men located at St. Louis: Walter T. Ray, Henry Kreisinger, Harry W. Weeks, Charles H. Green, Robert H. Kuss, Loyd R. Stowe, William M. Park, Ralph Galt, Fred O. Pahmeyer, Raeburn H. Post, George S. Pope, Gilbert E. Ryder, Fred J. Bird, Carl J. Fletcher, and Perry Barker.

Many of the opinions given in this volume are not shared by all the authors; some of them represent a compromise. The responsibility of selecting materials and deciding what views should be taken on many points naturally fell on Mr. Ray, who was the engineer locally in charge of steaming tests at St. Louis, and to him is to be charged the fault of any unjustified expressions of opinion or mistakes in text or figures.

It is realized that future work may show that some of the opinions advanced herein are faulty, and consequently the right is reserved to change them. Nevertheless, this work as a whole expresses the best present knowledge of the boiler division, and is given out for others to think about. It should be distinctly stated that the chemical division of this plant is in no way responsible for anything herein, although its members have been consulted on some points and have very kindly made many suggestions.

Special attention is called to the "General conclusions," page 174, and to the paragraphs entitled "Commercial considerations," page 177.

RELATIONS OF TEST DATA.

RATE OF COMBUSTION.

Fig. 1 should be considered in connection with fig. 2, the same tests being classified in both charts according to the pounds of dry coal burned per square foot of grate per hour. The figures in the small circles indicate the number of tests considered in determining the position of the points near which they are placed. In fig. 1 curve No. 1 is high for low rates of coal consumption, because it is hard to keep down the air supply. Curve No. 2 shows the per cent of stack loss. It drops at first because the air supply increases. (See curve No. 1.) It rises on the right because the gases leave the boiler at higher temperature, as shown by curve No. 3. The coals of the tests averaged on the left of the chart are in general of good quality and slower burning than those in the center; those on the right are somewhat lignitic in character. This perhaps explains why curve No. 3 is low in the center; the combustion-chamber temperatures were lower there, hence the flue temperatures were also lower. But, after all is said, the reason is in doubt, because the maximum flue-temperature range is only 50° F.

On comparing the flue-temperature curves of figs. 1 and 3 a difference will be seen in the left-hand ends. With reference to this curve in fig. 1, the coals toward the left end become better in quality and higher in "fixed carbon," so that although they burned slowly the combustion-chamber temperatures were fairly high, and consequently the stack temperatures were higher than in the center of the curve. With reference to the analogous curve of fig. 3, the coals to the left are both poorer and slower burning, and a larger air excess was used, relatively, which made the combustion-chamber temperature lower; consequently the flue temperature was lower. Further, the lower curve of fig. 1 is perhaps drawn a little too high at the left end, and that of fig. 3 a little too low.

Fig. 2 should be considered in connection with fig. 1. Little can be said of curve No. 1 (fig. 2), except that it rises slightly with increasing rates of combustion—about three to five times as much as the broken line just below, connecting the CO averages. The rising of both is perhaps a consequence of decreasing air supply per

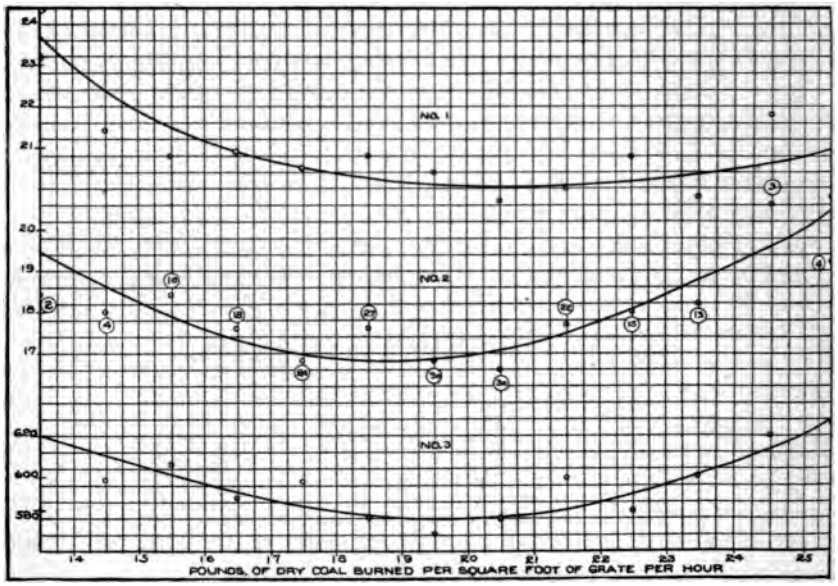


FIG. 1.—Relations of rate of combustion to pounds of dry chimney gases per pound of "combustible" (curve No. 1); per cent of loss up the stack, from heat balance (curve No. 2); and flue-gas temperature (°F.) taken under stack damper (curve No. 3). Classified on rate of combustion as basis; tests 126-355.

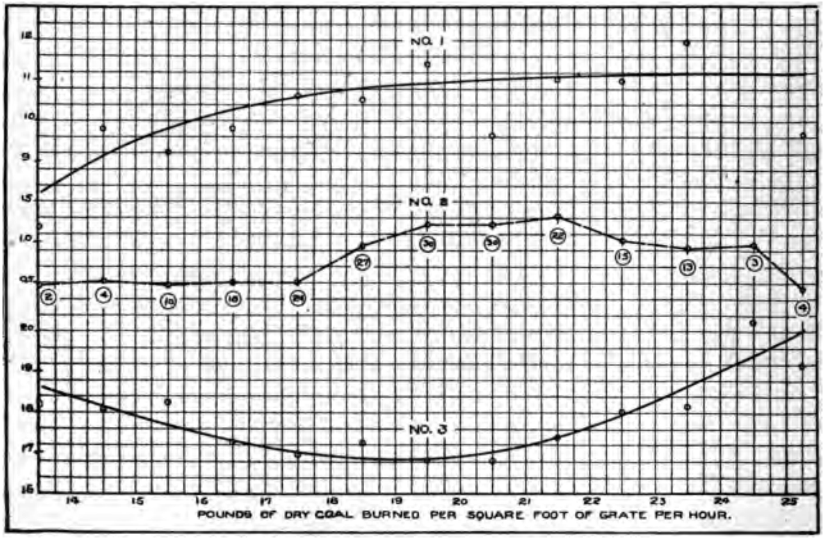


FIG. 2.—Relations of rate of combustion to per cent unaccounted-for loss (curve No. 1); per cent of CO loss (curve No. 2); and per cent of loss up the stack (curve No. 3). Classified on rate of combustion as basis; tests 126-355.

pound of "combustible," as indicated by curve No. 1 of fig. 1. Curve No. 3 of fig. 2 is a reproduction of curve No. 2 of fig. 1.

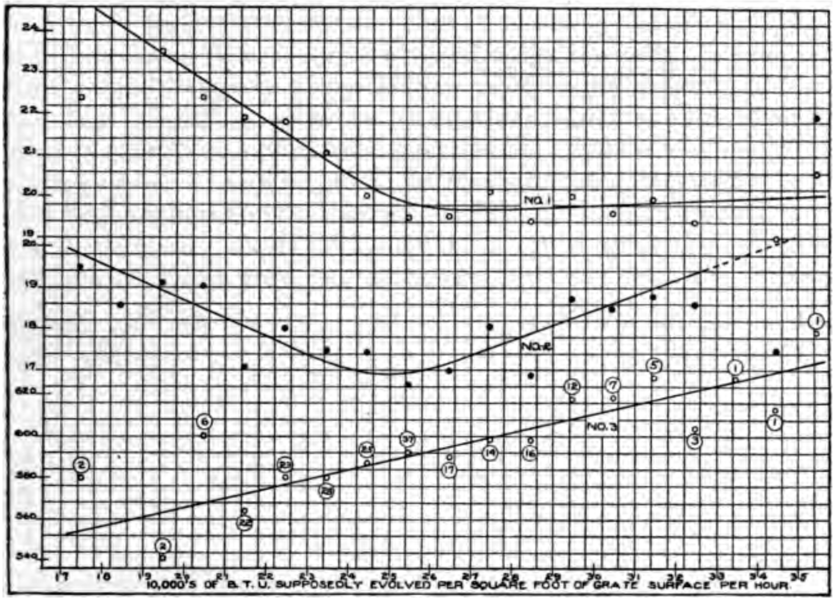


FIG. 3.—Relations of rate of heat evolution to pounds of dry chimney gases per pound of "combustible" (curve No. 1); per cent of loss up the stack (curve No. 2); and flue-gas temperature (°F.) (curve No. 3). Classified on rate of heat evolution as basis; tests 126–358.

SUPPOSED RATE OF HEAT EVOLUTION.

Fig. 3 should be considered in connection with fig. 4. In both charts the same tests are grouped according to the number of B. t. u.

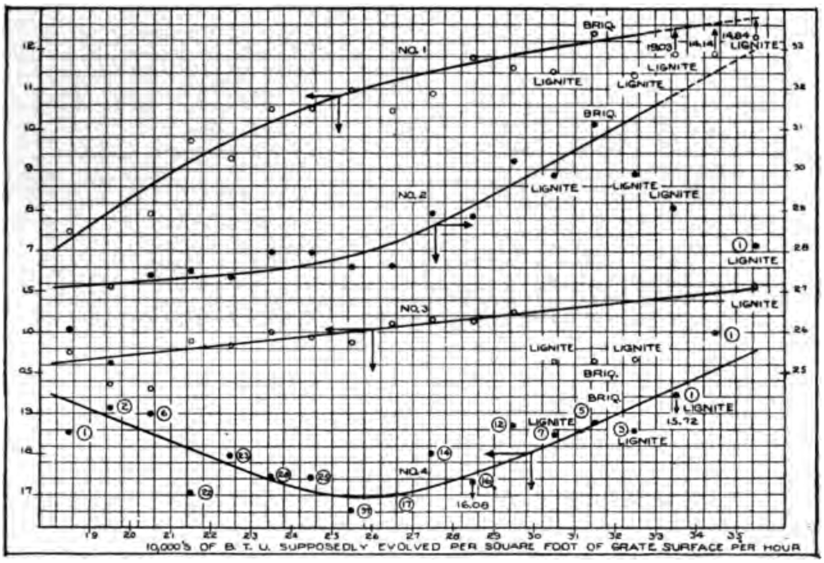


FIG. 4.—Relations of rate of heat evolution to per cent unaccounted for (curve No. 1); per cent unaccounted for plus per cent of loss up the stack (curve No. 2); per cent of CO loss (curve No. 3); and per cent of loss up the *stack (curve No. 4). Classified on rate of heat evolution as basis*; tests 126–358.

supposedly liberated per square foot of grate surface per hour. Had it been practicable, the six curves concerned would have been plotted on one chart. According to curve No. 1 the pounds of dry chimney gases per pound of "combustible" decrease rapidly at first, but for the right-hand half of the chart they remain constant. The left half of curve No. 2 shows a rapidly decreasing stack loss, which might be expected to remain about constant on the right, inasmuch as the pounds of dry chimney gases per pound of "combustible" remain constant. One explanation of its rising is that the circulation of water in the boiler fails to increase at as rapid a rate as the demands on it, in consequence of which the boiler is increasingly less efficient as a heat absorber, wherefore the gases escape at a higher temperature. This explanation would make curve No. 3 consist of two portions, the upward slope of the left half, which is due to rise of furnace temperature, being continued for the right half by the decreasing efficiency of the boiler.

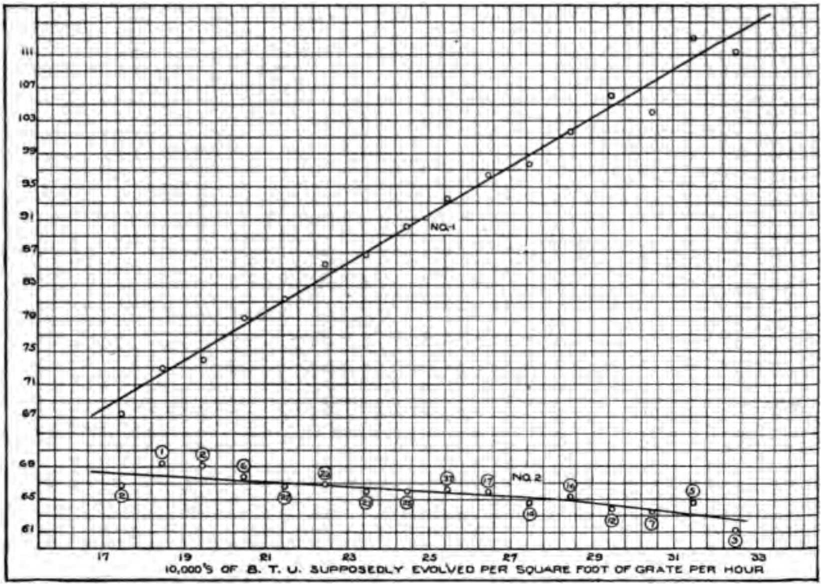


FIG. 5.—Relations of rate of heat evolution to per cent of rated capacity developed (curve No. 1) and efficiency 72* (curve No. 2), classified on rate of heat evolution as basis; tests 126–358.

For a comparison of the shapes of the flue-temperature curves of this chart and of fig. 1, see the text on the latter (p. 11).

Fig. 4 should be considered in connection with fig. 3. In both of these charts, as already stated, the same tests are classified on the basis of heat supposedly evolved; and here the emphasis is on the word "supposedly," for fig. 4 implies by circumstantial evidence that some of the fuel never burned. Curve No. 1, the per cent "unaccounted for," rises about 5 per cent, and curve No. 3, the per cent of CO loss, rises nearly 0.5 per cent along the same range of heat supposedly evolved. The implication is that the rise of CO loss is merely an indication of greater losses not ascertained, due probably to incomplete combustion.

Curve No. 4 in this figure is the same as curve No. 2 of fig. 3, a tentative explanation of which is given in the text relating to that figure (p. 13). The arrows on the curves indicate which coordinate scales are to be used with each curve.

Fig. 5 is based on about two hundred tests of coals from all parts of the country. It is not true to any great extent that the better coals are represented more in some parts of the curves than in others; therefore the following deductions are fairly reliable. The 10,000's of B. t. u. supposedly evolved per square foot of grate surface per hour was calculated by deducting the heat loss in CO and in combustible dropping through the grate from the heat value of the coal fired. Curve No. 1 shows that within the usual working range the capacity is very nearly a straight-line function of the heat supposedly evolved in the furnace. Curve No. 2 is especially significant, showing a decided falling off in efficiency 72*,[a] as the amount of heat supposedly evolved increases. By reference to the lower curve of fig. 6 it will be seen that the volume of the gases of combustion from 1 pound of carbon is nearly constant whatever the air excess used, providing this excess is within reasonable limits of operation. Therefore the volume of gases passing through the combustion chamber per

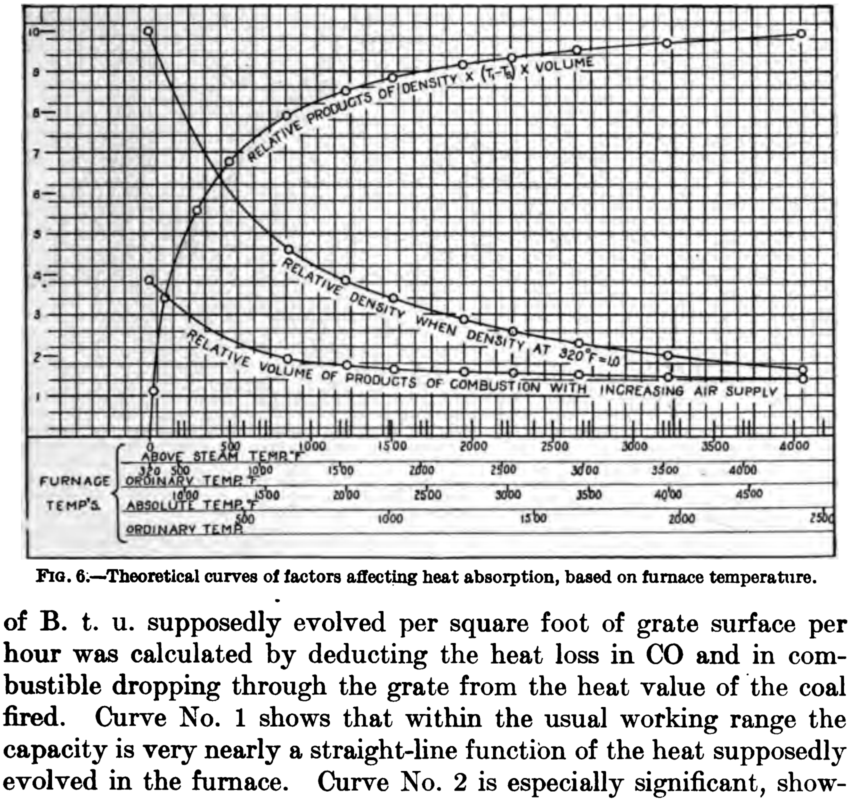


FIG. 6.—Theoretical curves of factors affecting heat absorption, based on furnace temperature.

---

[a] For definition of efficiency 72* see "Efficiencies" in the glossary (p. 181).

second is almost entirely a function of the coal burned, or, as given here, of the number of B. t. u. supposedly evolved per hour; whence the velocity of the gases as they pass from the fuel bed to the boiler entrance is proportional to the number of B. t. u. supposedly evolved. The emphasis is on the word "supposedly," for it is likely that the incompleteness of combustion increases as the time occupied by the gases in traveling from fuel bed to boiler decreases. This reduction of time for combustion is perhaps the reason for the common remark that when a combustion chamber is "worked too hard" its efficiency decreases; it may mix a large volume of gases as thoroughly as it does a fraction of the volume, but the time available for combustion is less.

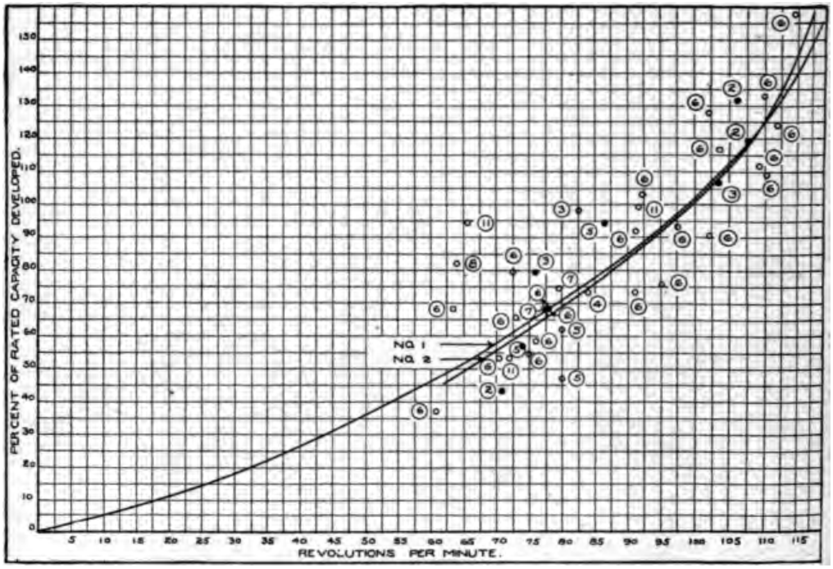


FIG. 7.—Velocity of water circulation in boiler as affected by rate of steaming: Curve No. 1, determined by classifying on revolutions per minute; curve No. 2, determined by classifying on per cent of rated capacity developed. Instrument for measuring circulation placed in first tube left of center in second row from bottom at rear of boiler.

Another probable cause of the drop of over-all efficiency (efficiency of furnace and boiler) is the fact that the circulation of the water inside of the boiler does not keep up with the capacity. Fig. 7 shows that the circulation of water does not increase in proportion to the capacity as it should. The consequence is that the water does not take the heat fast enough from the metal of the boiler, which therefore remains hotter at the higher capacities. When the heat-absorbing surface is at higher temperature less heat is available for the boiler, and hence the over-all efficiency drops. (See p. 137.)

On comparing the curves of capacity rise of figs. 5 and 8 it will be noticed that a given percentage change in B. t. u. supposedly evolved is accompanied by a much greater change in capacity than is the same percentage change in pounds of dry coal burned. The explanation is that as the pounds of dry coal burned per square foot of grate become less, the B. t. u. evolved do not on the average become much less, because some high-grade coals burn slowly; vice versa, some coals low in heating value burn rapidly. The capacity curve of fig. 8 may well have less slope than that of fig. 5. In studying the curves of fig. 8 it will also be noticed that when the pounds of dry coal burned per hour are doubled, efficiency 72* falls 5 per cent; whereas, referring to fig. 5, when the number of B. t. u. supposedly evolved is doubled, efficiency 72* falls 7 per cent, indicating both more incompleteness of combustion and poorer heat absorption.

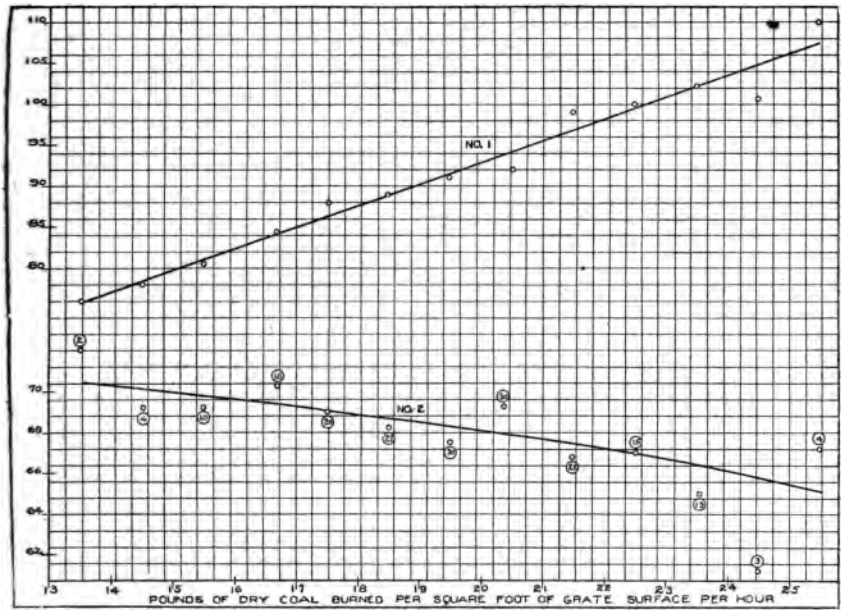


FIG. 8.—Relation of pounds of dry coal burned per square foot of grate to per cent of rated capacity developed (curve No. 1) and efficiency 72* (curve No. 2). Tests 126–355.

Curves determined by classification of various coals on the basis of pounds of dry coal burned per square foot of grate per hour are only approximate; those based on the heat supposedly (or ostensibly) evolved are of more value. The only correct classification would be on heat actually evolved as a basis. However, this involves the determination of the losses due to incomplete combustion of hydrocarbons and of solid particles of carbon escaping in smoke, and such determinations are very difficult to make, perhaps impossible.

COMBUSTION-CHAMBER TEMPERATURE.

Fig. 9 shows variation of temperature with firing in the Heine furnace. Variations of the temperatures in the fuel bed, over the fire, and in the combustion chamber are given with two very different coals. These temperatures were taken with the Wanner optical pyrometer (fig. 10), which was standardized before and after each series of observations. Every series of readings was taken without disconnecting the pyrometer from the battery after the standardization. Owing to the fact that only one pyrometer was available the temperatures were not taken simultaneously. The chart (fig. 9) shows clearly the three things following:

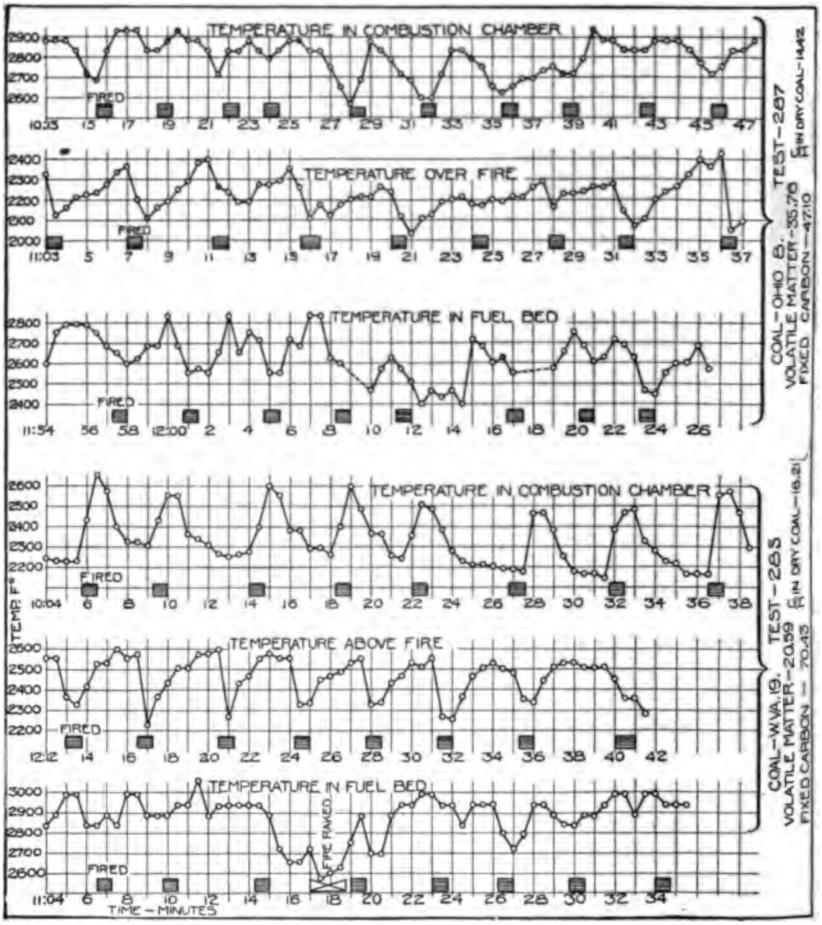


FIG. 9.—Variation of temperature with firing in Heine furnace.

1. During and shortly after each firing the temperature over the fire and to some extent the temperature in the fuel bed drops, and the temperature in the combustion chamber rises. The explana-

tion of this variation is that the distillation of "volatile matter" s a cooling process and is undoubtedly a partial cause of the drop of temperature in the fuel bed and over the fire, but the volatile matter distilled is carried into the combustion chamber, where it burns, causing a rise of temperature there.

2. The peaks in the curve for combustion-chamber temperature and the depressions in the curve for over-fire temperature are wider for Ohio No. 8, a coal high in volatile matter, than for West Virginia No. 19, a coal low in volatile matter, indicating that the volatile matter is distilled off and burned in shorter time in the West Virginia coal than in the Ohio coal.

3. Combustion-chamber temperature is much higher with Ohio No. 8 than with West Virginia No. 19, while fuel-bed and over-fire temperatures are higher with West Virginia No. 19 than with Ohio No. 8. This contrast indicates that most of the West Virginia No. 19 coal burns on the grate and only a little in the combustion chamber, while the opposite is true of Ohio No. 8.

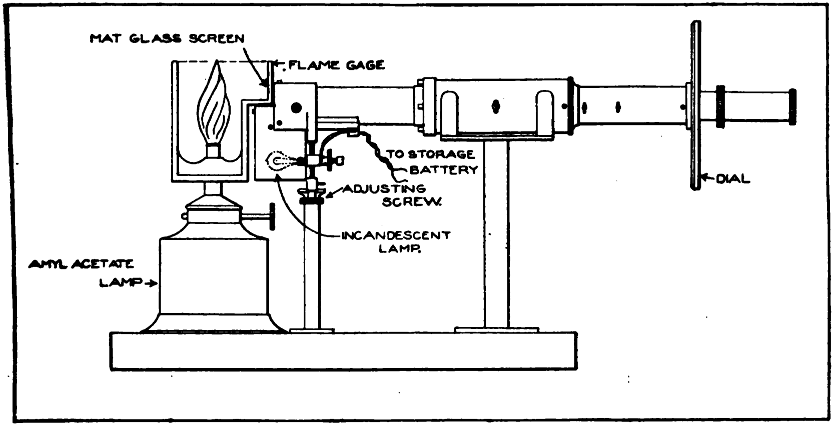


FIG. 10.—Wanner optical pyrometer in position for standardizing.

The two similar curves of fig. 11 are based on all tests (126–355) having combustion-chamber temperatures as read by the Wanner optical pyrometers. Coals from all parts of the country are included. To obtain the upper curve the tests were grouped according to pounds of dry coal burned per square foot of grate per hour; to obtain the lower curve they were grouped on 10,000's of B. t. u. supposedly evolved per square foot of grate per hour, the supposition being that all of the potential heat is liberated, after deducting for the loss of combustible in ash and for CO loss.

The rise in temperature throughout the whole range, for a doubling of the base values, is very nearly the same in the two curves. A significant feature of both curves is that the combustion-chamber temperature rises with the amount of heat liberated in the furnace; perhaps because conditions of combustion grow better at first, on advancing from poor coals at the left to the better ones in the center.

Curves No. 1 in fig. 1 and No. 1 in fig. 3 show the direct cause of the decreasing rise in combustion-chamber temperature.

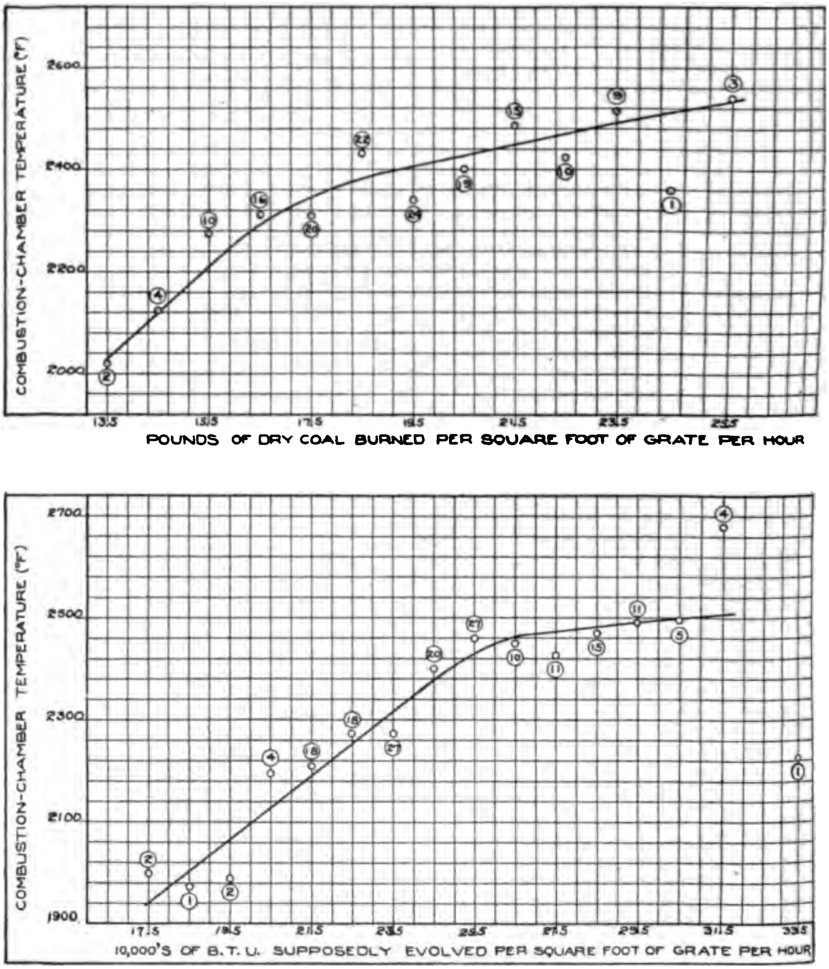


FIG. 11.—Combustion-chamber temperature as a function of pounds of dry coal burned per square foot of grate per hour, classified on basis of pounds of dry coal burned (upper curve); and 10,000's of B.t.u. supposedly evolved per square foot of grate per hour, classified on basis of 10,000's of B.t.u. supposedly evolved (lower curve). Tests 126–355.

The curves of fig. 12 are based on one class of coals—those from Illinois and Indiana. The only striking showing is that the code "boiler efficiency" (72*) is practically constant throughout the whole range of furnace temperature. All these coals are apt to evolve compounds difficult to burn, and thus it is that the lower the percentage of oxygen present the less complete the combustion, notwithstanding the higher temperature resulting. With these coals, therefore, the decreasing completeness of combustion in our apparatus with rise of temperature seems to offset the increasing efficiency of the boiler as a heat absorber, which is only about 10 or 12 per cent within the range 1,850° to 2,850° F., according to the chart on page 141.

In this chart, as in all others, where capacity is shown as a function of furnace temperature, the two rise together. This relation will be clear on remembering that much heat is absorbed through the tile roof of the furnace; and the greater the amount of coal burned the less in percentage will this absorption amount to, so that the temperature at the last point of combustion is higher.

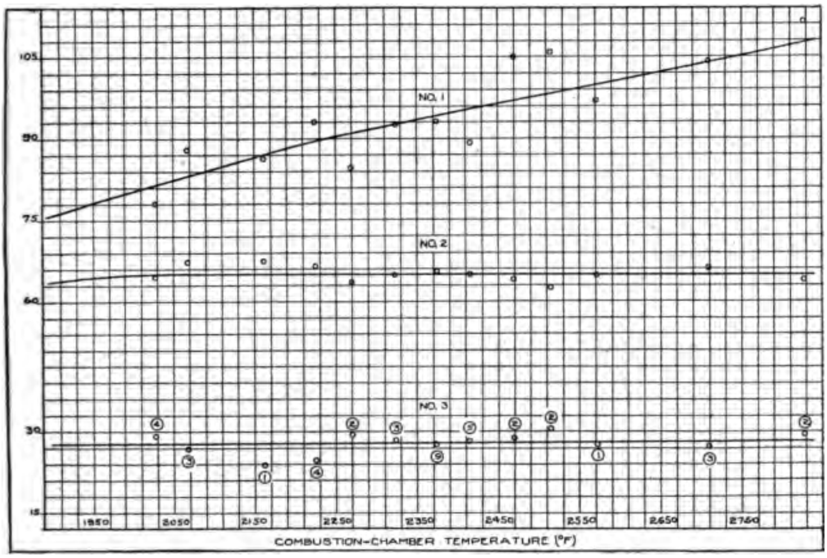


FIG. 12.—Relations of combustion-chamber temperature to per cent of rated capacity developed (curve No. 1); efficiency 72* (curve No. 2); and per cent unaccounted for plus per cent of loss up the stack (curve No. 3). Classified on basis of combustion-chamber temperature (°F.), Illinois and Indiana coals being used.

Fig. 13 is a companion to fig. 14, both charts being based on combustion-chamber temperature.

The arrows on the curves of fig. 13 indicate which coordinate scales are to be used with each. These thirty analyses were made at intervals of twenty minutes, on flue gases from the base of the stack, the combustion-chamber gases having been diluted with air by infiltration after entering the boiler. The curves of fig. 14 were computed on analyses of samples (taken half-hourly during about sixty tests) from the rear of the combustion chamber, through the water-jacketed gas sampler (fig. 15) described on page 154, so that these samples were probably undiluted.

As the temperature of combustion rises the oxygen percentage drops in a straight-line ratio and the CO_2 curve rises in nearly the same way; but the CO curve rises sharply after about 2,500° F. (1,370° C., the temperature indicated by curve No. 4 of fig. 14) has been reached. Of course the composition of the gases as affected by temperature probably varies from coal to coal. It should be remembered that on the whole the optical pyrometer probably indicated considerably lower temperatures than actually existed, because when burning short-flaming coals, or when running at the lower capacities, little flame was visible, and the instrument was pointed at a side wall visibly cooler than even the clay-tube tiles forming the furnace roof.

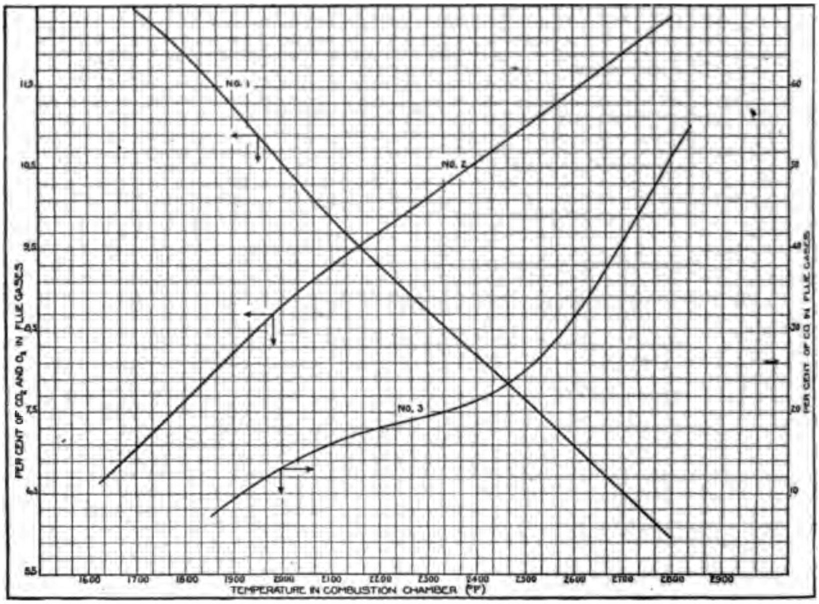


FIG. 13.—Relation of flue-gas composition to combustion-chamber temperature: Curve No. 1, O_2; No. 2, CO_2; No. 3, CO. Determined by averaging individual readings; tests 151-181.

Curve No. 1 of fig. 14 shows a gradual decrease in the Orsat totals as the temperature is raised, accompanied by reduced air supply. As the temperature rises the volume of hydrocarbons might be expected to increase, but their proportional volume would be so small that they would not affect this curve.

Fig. 16 is a graphic representation of the relation, in our apparatus, of combustion-chamber temperature to flue temperature for 212 tests, certain tests having doubtful readings being omitted. Both temperatures rise together. It is noticeable that the curve is less steep in the upper portion, which may be accidental, but indicates that at higher furnace temperatures the boiler absorbs a slightly greater percentage of the heat available to it above steam temperature than at the lower furnace temperatures; that is, the true boiler efficiencies are not always the same. But no reliable conclusion can be drawn. The significance of the curve is general only.

Fig. 17 shows a classification of 217 tests on many coals from all parts of the United States based on temperature in the rear of the combustion chamber. In general the poorer coals fall at the left of the chart. The most interesting showing (curve No. 1) is that the code "boiler efficiency" (72*) rises only 2 per cent as the combustion-chamber temperature rises from 1,800° to 2,700° F. This showing is in accordance with other charts and with the theory of boilers deduced on page 114, all being to the effect that a rise of about 1,000° F. in furnace temperature improves the efficiency of the boiler as a heat absorber only about 10 per cent. Most of this gain, however, is

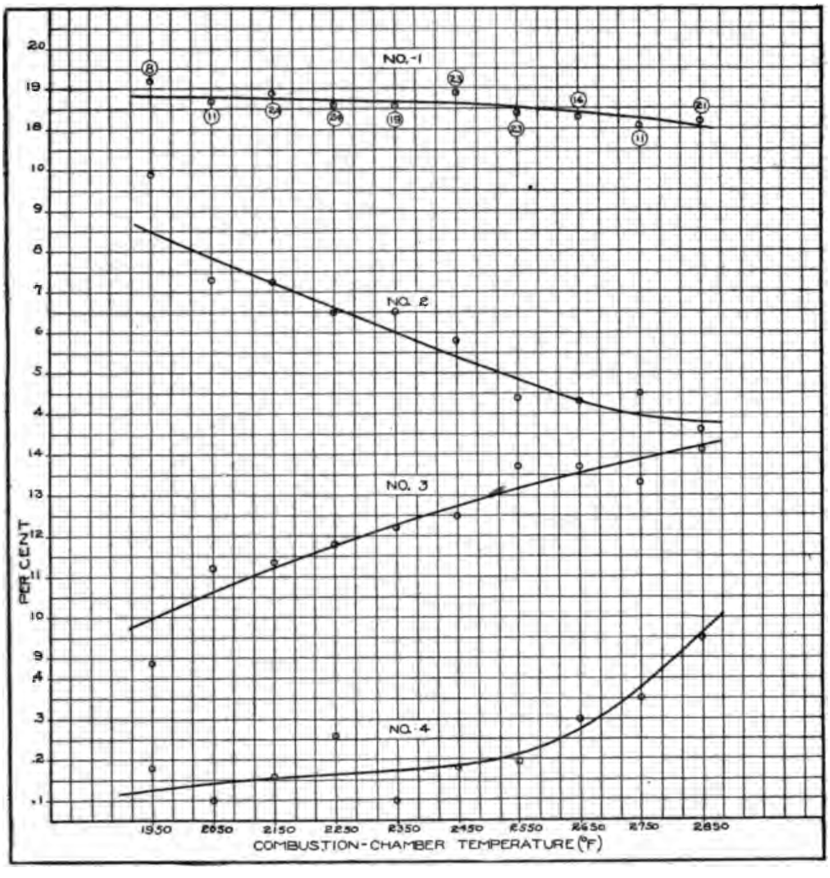


FIG. 14.—Relation of gas composition to temperature, both in rear of combustion chamber: Curve No. 1, CO_2+O_2+CO; No. 2, O_2; No. 3, CO_2; No. 4, CO. Samples of gas taken through water-jacketed iron pipe; tests 318–382.

offset by incompleteness of combustion chargeable to the restricted oxygen supply required to get the high temperatures.

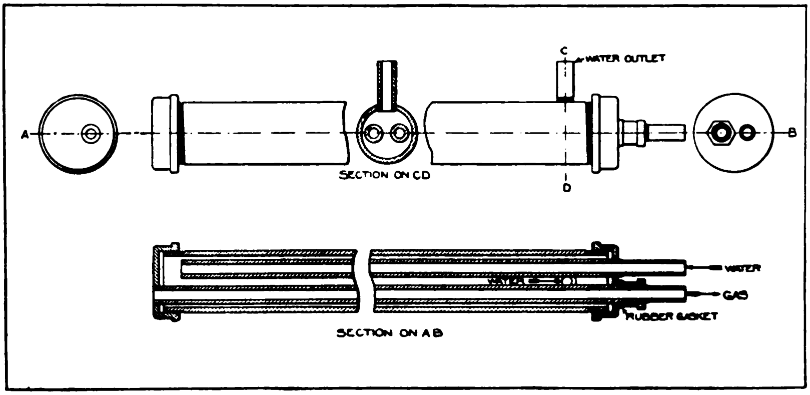


FIG 15.—Water-jacketed gas sampler.

Curve No. 2 shows a slight but persistent rise of CO_2 content in flue gases with increasing furnace temperatures, as is reasonable; it

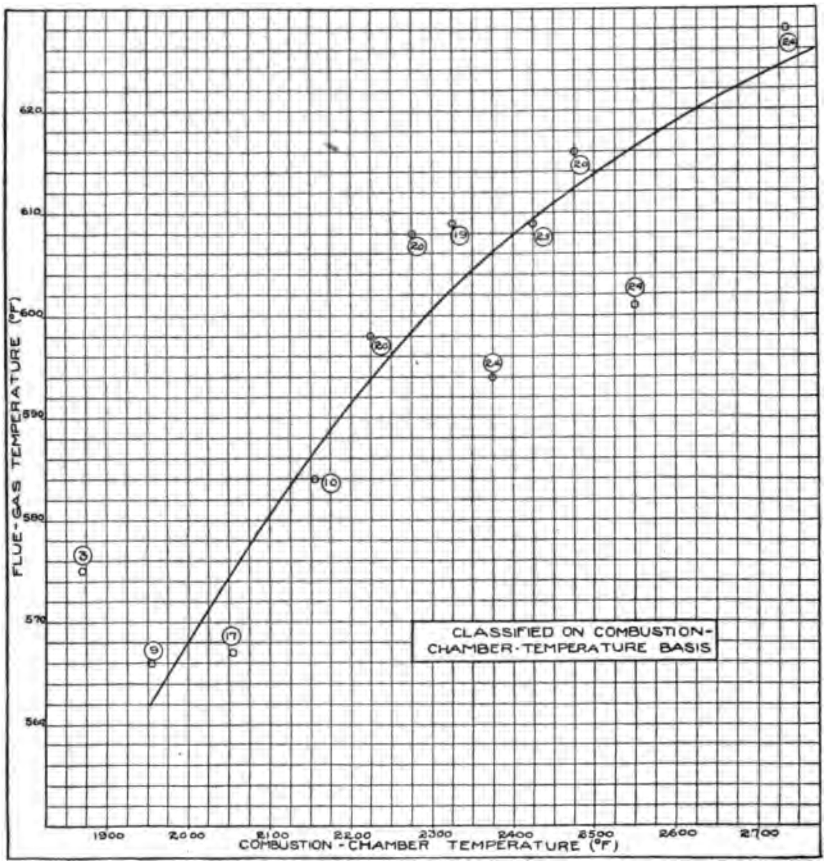


FIG. 16.—Relation of temperature in rear of combustion chamber to flue-gas temperature taken under stack damper; tests 150–400.

ought to be more marked. Air infiltration through the settings reduced the CO_2 percentage by 10 to 35 per cent in extreme cases.

Curve No. 3 shows a decided increase in the amount of steam made as the temperature rises. Since capacity is the comparative rate of absorption of heat by the boiler, it must necessarily increase with the rise of combustion-chamber temperature, if the equation used in the derivation of Perry's equation for true boiler efficiency, given on page 110, is true. The heat absorbed per second per unit of heating surface is

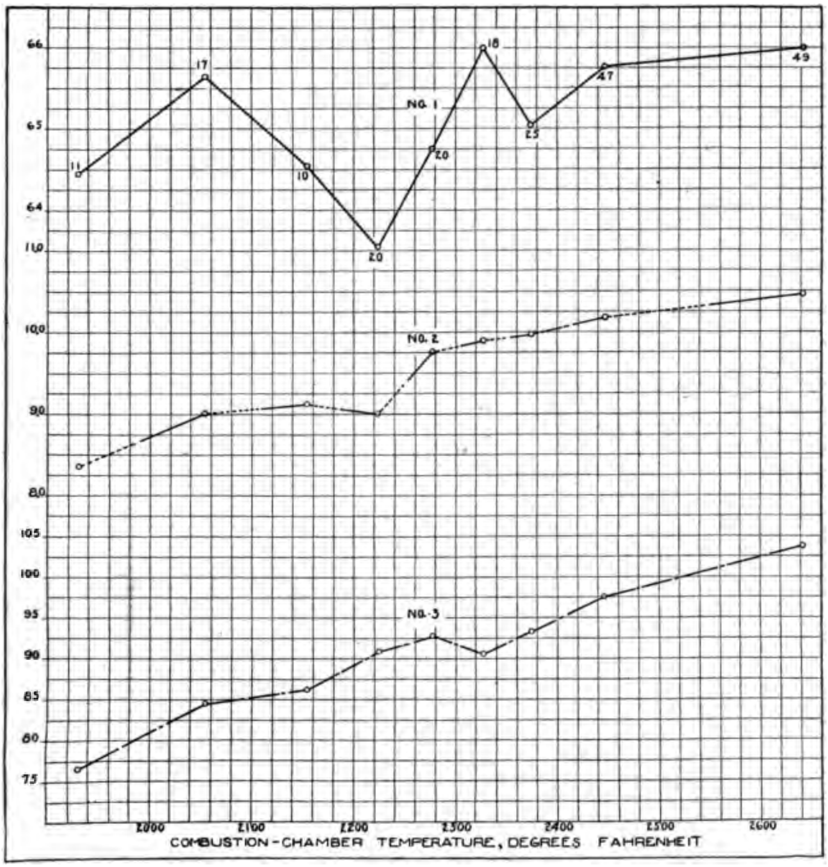


FIG. 17.—Relations of combustion-chamber temperature to efficiency 72* (curve No. 1); CO_2 in flue gases, samples taken in hood (curve No. 2); and per cent of rated capacity of boiler developed (curve No. 3). Classified on combustion-chamber temperature as basis; tests 150–400.

$$H = Cpv \ (T_1 - T_s).$$

Expressing the values of p and v in terms of T_1, we have

$$H = \frac{c}{T_1}.CT_1.C(T_1 - T_s) = K(T_1 - T_s).$$

The latter equation states that the capacity varies directly as the difference of the temperature of the furnace gases and the temperature of the steam.

As stated in the description of the baffle wall (p. 62), the construction and location were so chosen as to have the stream of gases leaving the furnace impinge against a solid part of the wall and break into many smaller streams, thus effecting mixing. It was intended to obtain a splashing effect similar to that seen when a stream of water is directed against a solid wall. That some such effect was attained was indicated by the high temperature taken through the opening just at the base of the bridge wall. This was invariably the highest temperature in the whole combustion space. Each of the temperatures given in the second column of the following table is the average of ten readings taken with the Wanner pyrometer at five different places in the furnace. The readings were taken successively through the side-wall openings from front to rear, so that the averages may be considered to represent simultaneous temperatures at all five places. Twenty-four readings were also taken in the same way by an exposed platinum and platinum-rhodium couple, connected to a galvanometer reading in degrees centigrade, giving the average temperatures at four places, as shown in the third column of the table.

Furnace temperature readings (test 359).

Place.	Wanner pyrometer.	Galvanometer.
	°*F.*	°*C.*
Fuel bed	2,470	913
Over fire	2,586	....
Over bridge wall	2,826	1,075
Base of bridge wall	2,989	1,280
Rear of combustion chamber	2,447	1,035

The temperatures taken with the thermoelectric couple have only relative value, and are in fact much too low, the galvanometer having been recently repaired so that the divisions on the scale were not true degrees centigrade. The couple used had an exposed junction projecting from the end of a $\frac{3}{8}$-inch iron pipe.

A. S. M. E. CODE BOILER EFFICIENCY (72*).

Fig. 18 consists of two charts. In the upper chart 293 tests are grouped according to efficiency 72*, the averages being plotted for each group of the percentages of CO and. CO_2. All the higher efficiencies have low CO values and the lower efficiencies high CO values. The higher efficiencies have higher CO_2 values than the lower efficiencies, of course, though not much higher. The CO curve (No. 1) should be compared with curve No. 3 of fig. 19, which is based on the same tests. The implication is the same—that high CO is a danger signal.

In the lower chart the same 293 tests are classified according to the percentage of CO_2 in the flue-gas analyses. The points plotted are the averages of the code "boiler efficiencies" (72*). It is evident that when once the CO_2 content gets beyond 9 per cent at the rear of the combustion chamber only about 1 per cent more—at most only 2 per cent—is to be gained by raising it higher. The percentage of CO_2 in the furnace and boiler were really about 20 per cent higher on the average than here mentioned because of an air infiltration through the settings amounting to 10 per cent, or 50 per cent of the volume present in the rear of the combustion chamber.

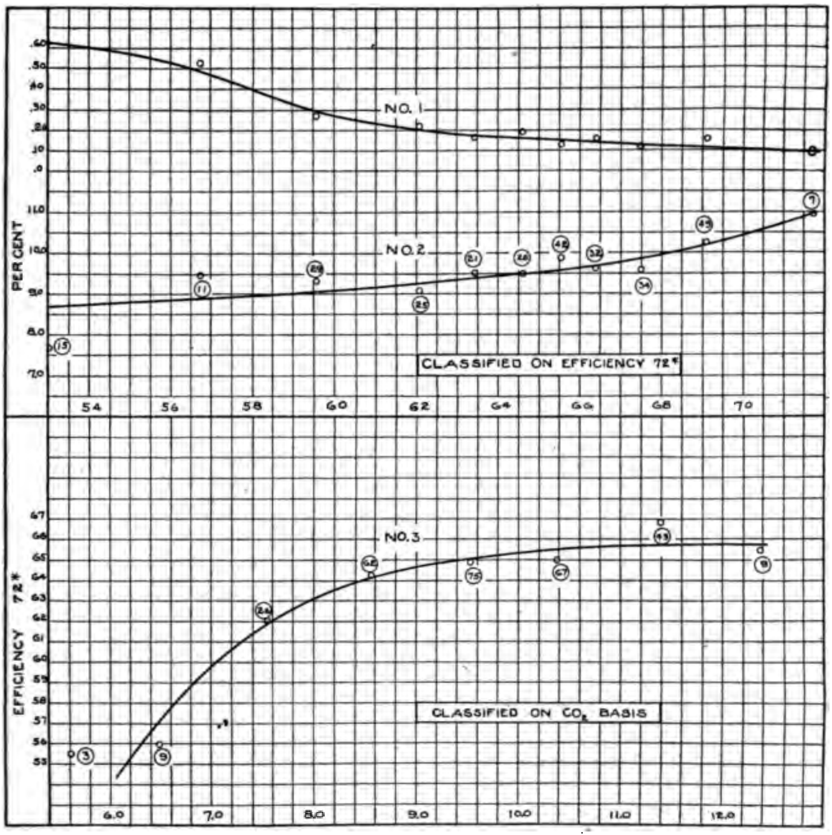


FIG. 18.—Relations of efficiency 72* to per cent of CO, stack sample (curve No. 1); per cent of CO_2, stack sample (curve No. 2); and per cent of CO_2 (curve No. 3). Tests 89–401.

There is a general resemblance between curve No. 3 and the curve in fig. 20 labeled "Heat absorption as affected by combustion-chamber temperature." The latter curve is closely dependent (theoretically) on the CO_2 content, and it probably is no mere coincidence that the two curves have much the same shape. The same remark applies to the analogous curve of fig. 6 (p. 15).

Fig. 21 represents an attempt to find relations between per cent of sulphur in coal (separately determined), per cent of clinker in refuse, and "boiler efficiency" (72*). It is agreed that clinkering is a consequence of the effects of high fuel-bed temperature on such of the mineral constituents in the ash as will form a fusible mixture. It must be remembered that the fineness of subdivision and the distribution of the minerals throughout the coal are probably as important as the temperature and chemical composition. Thus it is that "sulphur" (pyrites) in the form of little balls is nearly harmless; in the form of veins or layers it is liable to cause trouble; but in the

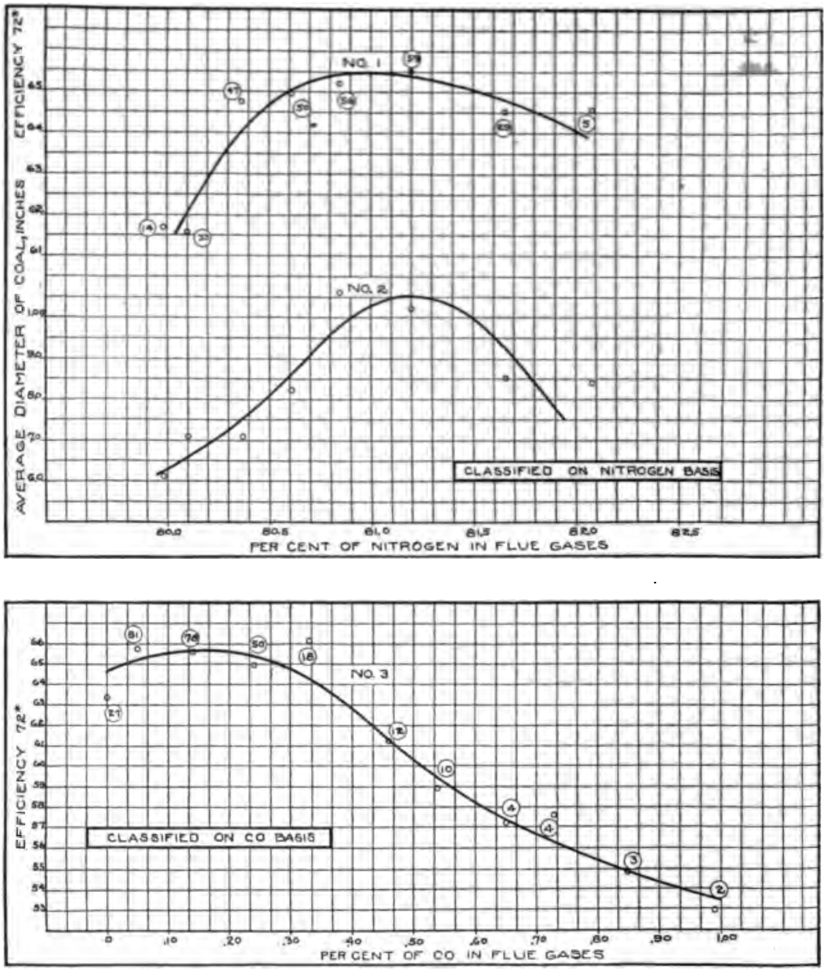


FIG. 19.—Relations of nitrogen to efficiency 72* (curve No. 1); nitrogen to average diameter of coal (curve No. 2); and per cent of CO to efficiency 72* (curve No. 3). Tests 89–400.

form of "black sulphur," so finely distributed as to be invisible, it is most troublesome. From these remarks it is evident that the boiler room is not the proper place to make a scientific study of clinkering, but that it should be taken up in the laboratory along the following lines: (1) Ash analyses; (2) experimental determination of fusing points; (3) ascertaining the distribution of the ash and its various constituents throughout the coal.

To determine the fusing point of ash, all the combustible in the ash should be burned out at the lowest possible temperature. The ash could then be made into Seger cones, which could be heated in a furnace and the temperature read with a pyrometer.

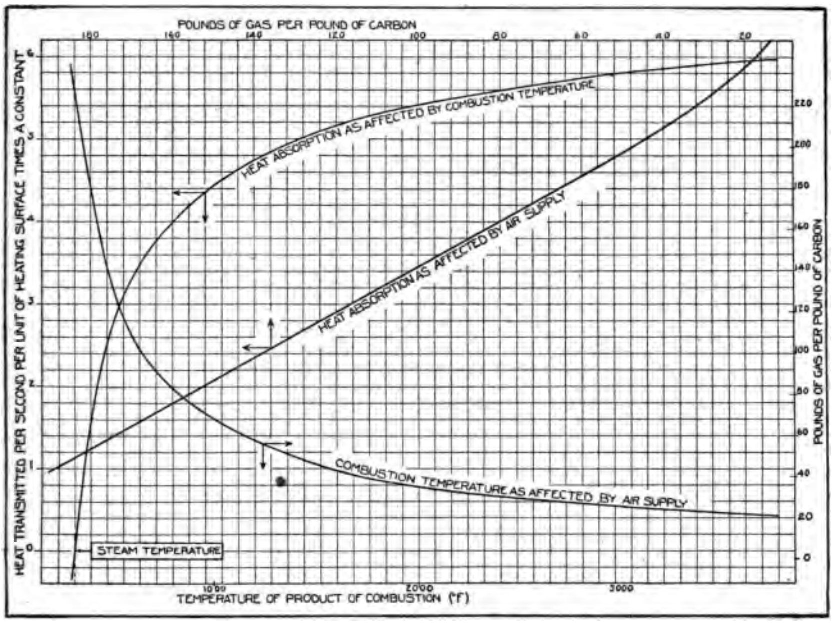


FIG. 20.—Theoretical curves of heat absorption as affected by air supply. Arrows on curves show respective coordinates.

The distribution of the ash might be determined by laboratory washing processes. One method of doing this would be to grind the coal to a certain fineness and float it successively on solutions of potassium hydroxide of varying per cent dilution.

The chemical division, under the guidance of N. W. Lord, is carrying on some of the above investigations, and the writer is indebted to him for explanations of methods.

Notwithstanding the probability, implied above, that sulphur does not have a great deal to do with the formation of clinker, it was thought well to find out whether in general it helps or hinders efficiency.

The upper half of fig. 21 contains tests classified according to "boiler efficiency" (72*). In curve No. 1 each point is the average of the per cent of clinker in refuse for each group and in curve No. 2 of the per cent of sulphur in coal. According to curve No. 1, the coals giving high efficiencies are apt to form a very slightly smaller percentage of clinker, and according to curve No. 2 the high-efficiency tests are likely to be made on coals low in sulphur, this relation being rather marked. However, it must be remembered that high-sulphur coals are usually high in ash also.

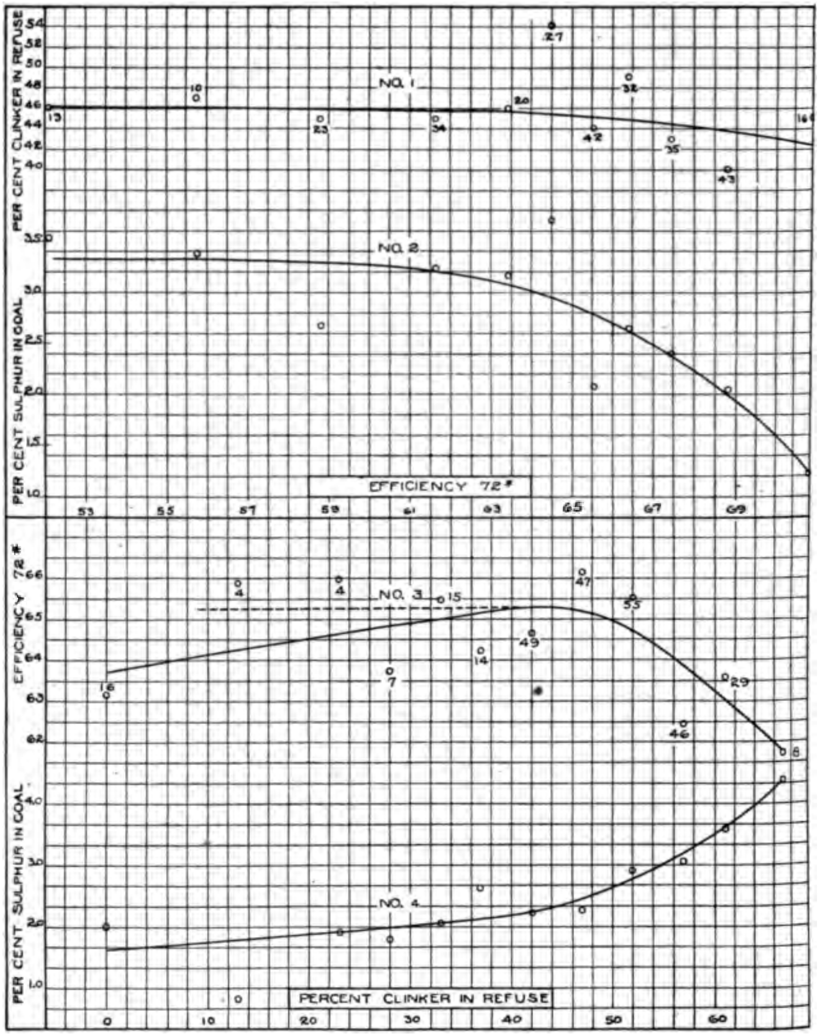


FIG. 21.—Relations of efficiency 72* to per cent of clinker in refuse (curve No. 1); efficiency 72* to per cent of sulphur in coal (curve No. 2); per cent of clinker in refuse to efficiency 72* (curve No. 3); and per cent of clinker in refuse to per cent of sulphur in coal (curve No. 4) Curves Nos. 1 and 2 classified on efficiency 72* basis; Nos. 3 and 4 on clinker basis. Tests 89–401.

The indications of the curves of fig. 21, regarding the effect of sulphur, are at slight variance with those of fig. 28 (p. 43).

Careful records were kept regarding the appearance and distribution of the ash of each coal, but time has not been found to study and classify the information.

The lower half of fig. 21 was obtained by classifying the same tests according to the per cent of clinker in the refuse, which was done in order to determine the effect of clinker on efficiency. In curve No. 3 the heavy line gives full weight to 16 tests on coals, some of which were of lignitic character and formed no clinker, but gave rather low efficiencies. Even considering this full portion of the line, instead of the dotted portion above it, the clinker hardly affects efficiency until it reaches about 45 per cent, above which there is a rapid drop. Curve No. 4 indicates that high percentage of clinker accompanies high sulphur content; but it must be borne in mind that perhaps sulphur of itself has little to do with fusibility of ash and that the iron which is combined with a part of the sulphur is only one of the factors in clinkering.

The classification of the relation of efficiency 72* to the sum of the percentages of ash and sulphur, given in the following table, was made by using 92 tests on coals from Illinois, Indiana, and Kentucky, all of which are much alike. To be more certain, the work was done in two ways—by classifying the tests in groups of efficiencies and in groups of percentages of ash plus sulphur. The latter classification is not here given. The tests selected lay between Nos. 126 and 401 and were more comparable than if some earlier ones had been included.

There was no special reason for using the sum of the percentages of ash and sulphur except that it is sometimes stated without qualification that ash and sulphur affect efficiency. The conclusion is that the sum of ash and sulphur has no visible effect on efficiency 72*.

Classification of average ash plus sulphur on basis of efficiency 72 (Indiana, Illinois, and western Kentucky coals).*

	Efficiency 72*.						
	Up to 57.5.	57.5 to 60.0.	60.0 to 62.5	62.5 to 65.0.	65.0 to 67.5.	67.5 to 70.0.	70.0 up.
Number of tests	1	5	8	28	29	17	4
Average efficiency 72*	55.93	58.92	61.39	63.97	66.16	68.50	70.82
Average ash plus sulphur in dry coal	18.89	14.22	15.93	16.65	16.60	15.41	15.86

It was early noticed that the second test on a coal was generally no better as to over-all efficiency than the first. An inspection of the first hundred tests or so confirmed this opinion. Only tests made on the same shipment of the same commercial grade of coal were compared; for instance, if the first test was run on a nut size and the second on screenings, these tests were not used.

It was usually the case that the man running the fire learned much the first day which was beneficial to the later tests, but which was more than offset by other factors. For instance, owing to the position of the chutes that discharge coal into the boiler-room bins and to the sloping bottoms of the bins the largest coal is obtained the first day.

The following tabulation has been made on 196 tests and shows that one test on a coal is sufficient:

Averages of five series of tests for efficiency 72.*

	First tests.	Second tests.	Third tests.	Fourth tests.	Fifth tests.
Number of tests averaged	77	77	32	8	2
Average efficiency 72*	66.05	66.02	65.87	64.99	67.76

The efficiency 72* is that of the furnace and boiler combined, figured from pounds of "combustible" actually ascending from the grate.

MOISTURE IN COAL.

The two curves of fig. 22 are based on the same tests. The upper curve is somewhat misleading, because the poorer coals contained on the average more free moisture. Just what effect different percentages of free moisture would have in the case of the same coal, reckoning above dry coal, is still undetermined. This line of investigation will be taken up in the future. This curve merely indicates that coals high in free moisture should be suspected and watched, especially when burning them in furnaces of this particular type.

The great variability of the lower curve suggests that ordinary percentages of ash have little effect on efficiency, and that the best efficiencies are obtained only with low ash. No doubt other appliances and furnaces are available which would give better results on dirty coal than have been obtained by hand firing on a plain grate.

ASH AND CLINKER.

In order to eliminate one nonuniformity in testing for the effect of percentage of ash in coal as fired on efficiency 72*, only the coals from Illinois, Indiana, and western Kentucky were used. The subjoined table shows that for the range of ash in these coals the efficiency is almost constant.

Fig. 22, in which all the coals tested are classified, shows the effect on efficiency 72* of percentage of ash in coal as fired.

Classification of efficiency 72 on basis of per cent of ash (proximate analysis) in coal as fired (Indiana, Illinois, and western Kentucky coals).*

	Per cent of ash.							
	4 to 6.	6 to 8.	8 to 10.	10 to 12.	12 to 14.	14 to 16.	16 to 18.	18 to 20.
Number of tests	3	10	22	22	19	11	3	2
Average per cent of ash in coal as fired	5.68	7.26	8.99	10.86	13.14	15.11	16.81	18.81
Average efficiency 72*	65.53	65.81	64.02	65.01	65.65	66.08	67.03	65.27

The subjoined table indicates that very few coals burn without clinker. Of the few which do, those high in sulphur are lignites. Pennsylvania No. 7, of test 307, was exposed to weather for four and a half months before it was tested. The same coal when tested (test 198) soon after it arrived at the plant formed clinker amounting to more than one-half of the total ash.

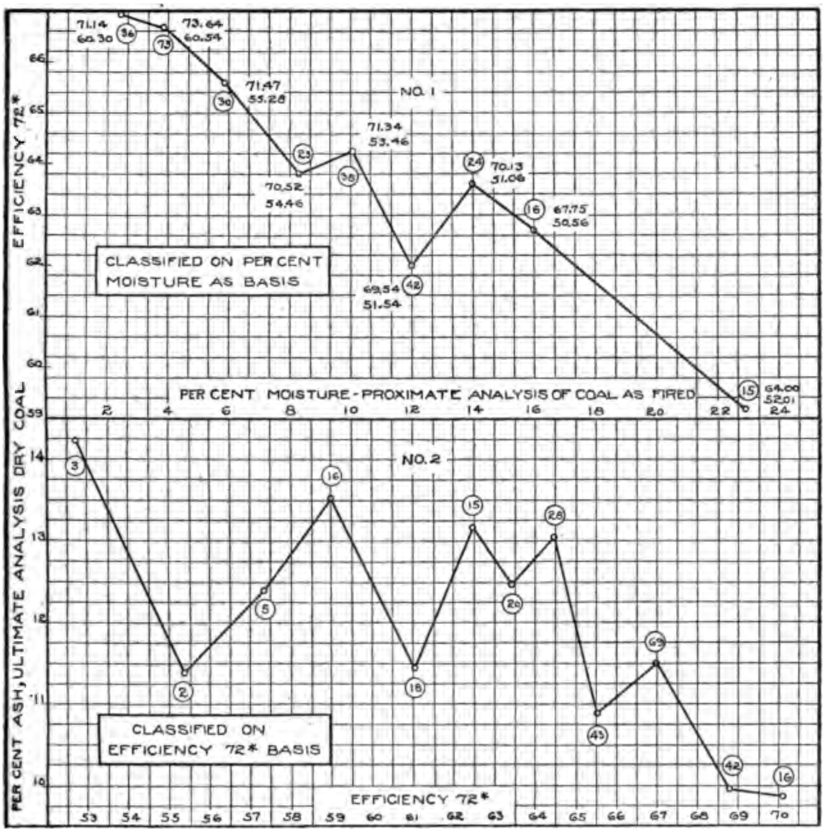


FIG. 22.—Relations of per cent of moisture (proximate analysis) in coal to efficiency 72*, as shown by tests 101–400 (curve No. 1); and of efficiency 72* to per cent of ash (ultimate analysis) in dry coal, as shown by tests 120–400 (curve No. 2).

The temperatures at which the lignites were burned are rather low, and it is probable that they might have clinkered with high temperatures. The conclusion must not be drawn that some coals represented in this table did not clinker because they were low in sulphur.

Coals burned without producing clinker.

Test No.	Coal.	Combustion-chamber temperature.	Sulphur, separately determined in coal as fired.	Test No.	Coal.	Combustion-chamber temperature.	Sulphur, separately determined in coal as fired.
		°*F.*	*Per cent.*			°*F.*	*Per cent.*
172	Brazil No. 1	1,900	3.02	387	New Mexico No. 5	2,371	0.81
173	.....do	1,858	4.53	389	New Mexico No. 3 B	2,225	.74
196	Wyoming No. 2 B	1,950	4.78	391	.....do	2,432	.69
210	.....do	2,200	4.37	392	New Mexico No. 3 B (washed)	2,420	.75
213	.....do	2,142	5.52				
290	Washington No. 1 B	2,047	.69	396	New Mexico No. 3 A	2,333	.74
291	Texas No. 4	2, 19	.80	397	New Mexico No. 4 A	2,336	.61
298	.....do	2,269	.79	398	New Mexico No. 4 A (washed)	2,534	.66
307	Pennsylvania No. 7	2,220	2.36				

The curves of fig. 21 (p. 30) show that the efficiency as based on the coal ascending from the grate (72*) is not influenced by the per cent of clinker in refuse until the latter exceeds 45 per cent, after which the efficiency drops 3 or 4 per cent. Inasmuch as clinker may prevent fine coal from falling through the grate, the same classification was made to learn how per cent of clinker in refuse affected code item 73, which is the over-all efficiency of boiler and grate. This classification is given in the following table. There is only a slight tendency for efficiency to decrease at the high clinker values, whence the deduction can be made that although clinker may hinder combustion it saves almost enough fine coal to compensate for its bad effects. However, it should be noted that the tests showing extremely high clinker were few in number.

Classification of efficiency 73 on basis of per cent of clinker in refuse.

	Per cent of clinker.								
	Under 30.	30 to 35.	35 to 40.	40 to 45.	45 to 50.	50 to 55.	55 to 60.	60 to 65.	65 up.
Number of tests	30	13	12	44	47	55	36	26	7
Average per cent of clinker in refuse	11	33	37	42	47	52	57	61	67
Average efficiency (item 73)	62.95	65.19	63.57	63.96	64.65	64.31	62.95	63.16	62.45

Clinker is an interesting item, as it gets the blame for many things. Figs. 21 and 23 treat some phases of the subject, but the subjoined table has not been plotted.

The impression is general that iron causes clinkering. The tabulation partially confirms the impression, as the percentage of iron in dry coal increases in general with the clinker. Nevertheless iron is only one cause of clinker, and its presence in considerable quantity does not necessarily mean that a coal will clinker.

Classification of per cent of iron on basis of per cent of clinker in refuse.

	Per cent of clinker in refuse.							
	Under 30.	30 to 35.	35 to 40.	40 to 45.	45 to 50.	50 to 55.	55 to 60.	Over 60.
Number of tests	3	5	2	6	14	17	7	5
Average per cent of clinker in refuse	12	32	38	42	47	52	57	63
Average per cent of iron in dry coal	1.01	0.95	1.76	1.54	1.02	1.69	1.81	2.34

The curves of fig. 24 present a classification of tests on the basis of per cent of clinker in refuse. (See also discussion of fig. 28, p. 43.) The table on page 41 was compiled with the object of ascertaining whether any relation exists between the amount of clinker and the average size of the coal and shows that there is very little such relation. One significant feature shown is that the highest value of average size of coal is grouped with the highest value of per cent of clinker, and vice versa.

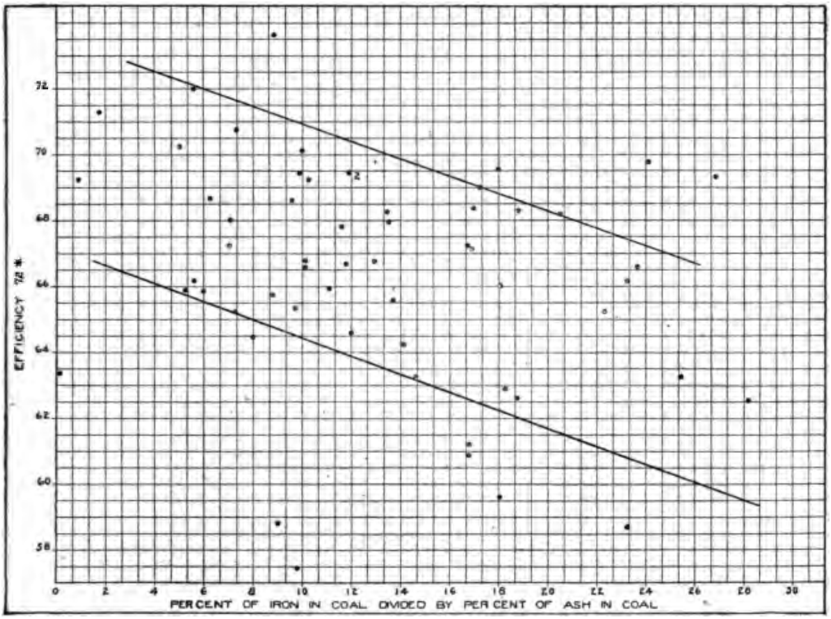


FIG. 23.—Relation between ratio of per cent of iron in coal to per cent of ash in coal (proximate analysis) and boiler efficiency 72*.

The curves of fig. 25 show a classification of coals on the basis of carbon-hydrogen ratio. It may be noted that as the per cent of clinker decreases the per cent of CO loss decreases; in fact, the two curves are nearly parallel. The efficiency 72* curve varies inversely with the CO loss and clinker curves. The curve of average diameter on this chart shows that the largest sizes of coal and highest values of clinker are grouped together. The pounds of dry chimney gases per pound of "combustible" are almost of constant value. This relation is a corroboration of the text relating to fig. 28 (p. 43) regarding incomplete combustion and the decrease of efficiency 72* by the formation of clinker.

It is also likely that although the size of coal burned can not be determined by the amount of clinker formed, it is possible to estimate the amount of clinker that will result from burning different sizes of the same kind of coal. With any one kind of coal the amount of clinker formed is related to the distribution and the nature of the ash. Generally the ash is distributed through the coal in thin or thick layers. In coal which is crushed to small sizes these layers become separated from the coal; and when such crushed coal is thrown into the furnace, the particles of ash, being heavier than the coal, soon pass down into the colder layers of ash and fuel near the

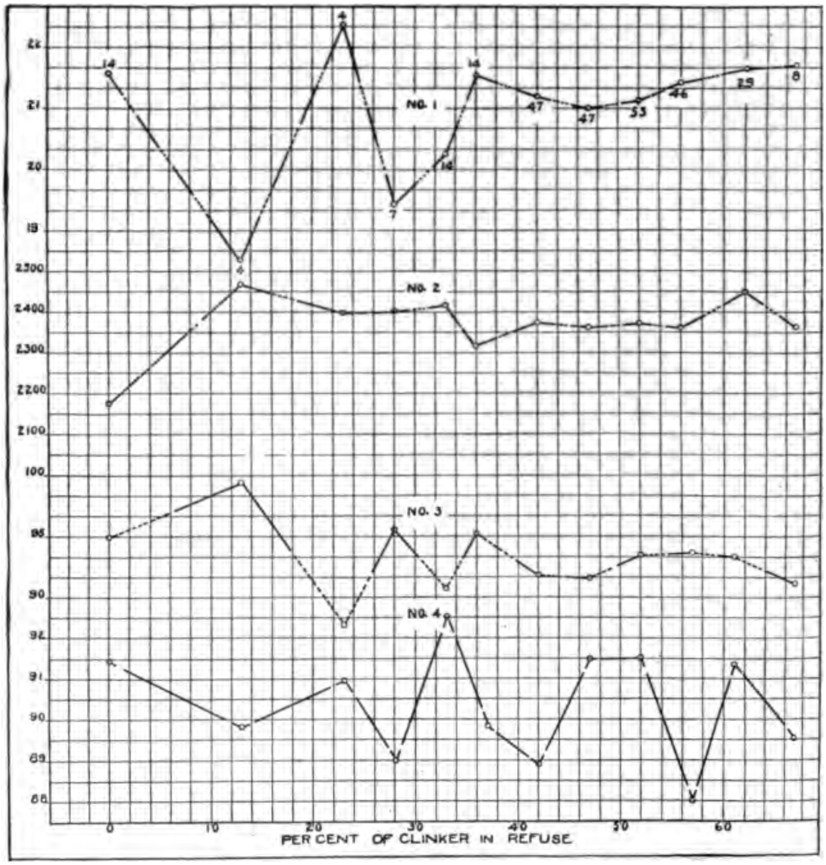


FIG. 24.—Relations of per cent of clinker in refuse to pounds of dry chimney gases per pound of "combustible" (curve No. 1); combustion-chamber temperature (°F.) (curve No. 2); per cent of rated capacity developed (curve No. 3); and per cent of completeness of combustion (E_3) (curve No. 4). Tests 89–400.

grate and are therefore not heated to a temperature high enough to melt. In large-sized coal, on the other hand, the ash remains more in the lumps of coal and is held near the top of the fuel bed, where the temperature is usually above the melting point of the ash.

In plotting the curves of fig. 23 (p. 35) an attempt was made to determine the effect on efficiency 72* of per cent of iron in coal as fired. The ratio of iron in coal to ash in coal was taken as a basis, because it seemed that there was a close relation between the two; for instance, a large amount of ash and a high iron value would not be expected to cause as much trouble as a high iron value and a low percentage of ash.

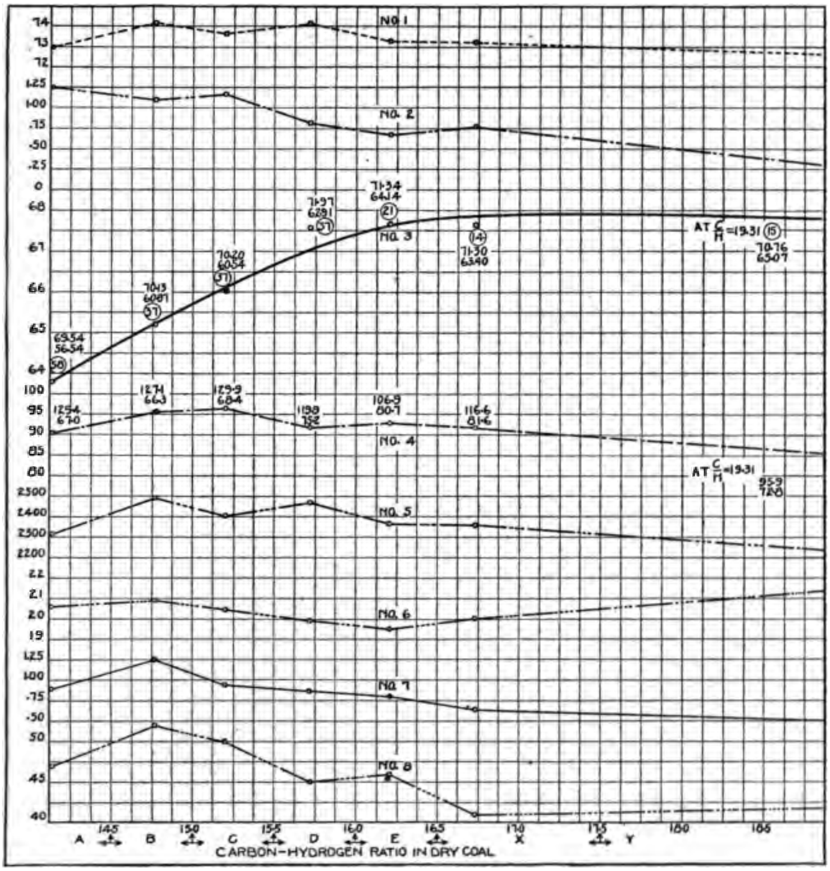


FIG. 25.—Classification based on carbon-hydrogen ratio in dry coal: Curve No. 1, theoretical efficiency of boiler as a heat absorber at various temperatures; No. 2, per cent of CO loss; No. 3, efficiency 72*; No. 4, per cent of rated capacity developed; No. 5, combustion-chamber temperature (°F.); No. 6, pounds of dry chimney gases per pound of "combustible;" No. 7, average diameter of coal; No. 8, per cent of clinker in refuse. Tests 120–380.

Since only about 60 iron determinations were available, it seemed best to plot the individual points instead of average points. The slope of the band inclosing the points shows that the ratio of iron in coal to ash in coal has perhaps a slight effect on efficiency 72*. This effect is probably due to the formation of nonporous clinker.

The relation of iron in dry coal to clinker in refuse was ascertained by classifying the data on the basis of per cent of clinker, the results showing a large increase in per cent of iron as the per cent of clinker increased. See text relating to figs. 24 and 28 (pp. 43–44) and table on page 35.

L. H. Hartley Smith, writing to Power in 1905, called attention to the fact that the refuse drawn from the ash pit and off the grate when cleaning fires seemed to contain less carbon when the percentage of clinker was high. An inspection of the data of a few of our tests confirmed the observation, and later the following tabulation was made on about 370 tests. The probable explanation is that when clinker forms on the grate it keeps fine coal from falling through.

Classification of per cent of combustible on basis of per cent of clinker in refuse.

	Per cent of clinker.								
	Under 30.	30 to 35	35 to 40.	40 to 45.	45 to 50.	50 to 55.	55 to 60.	60 to 65.	65 up.
Number of tests	38	16	16	56	59	70	59	45	11
Average per cent of clinker	10.9	32.4	37.0	42.1	47.1	52.0	57.6	61.3	66.9
Average per cent of combustible in refuse	25.65	28.29	24.10	23.70	21.75	20.43	18.53	19.40	15.52

Sulphur is an undesirable element in coal. It generally occurs in combination with iron, as iron pyrites, and in combination with calcium, as calcium sulphate or gypsum. Pyrites can readily be recognized by its heavy weight, bright brasslike color, and crystalline structure. The calcium sulphate occurs in small, thin, white flakes, more or less transparent. Of the two sulphur compounds, the pyrites is generally contained in larger quantity in coal, and is harmful because it increases the tendency of the coal to clinker. The clinkering is especially bad if the percentage of ash is small in proportion to the sulphur. In such coals the pyrites and the ash fuse together and form a thin layer of solid clinker, which effectively stops the passage of air through the grate, thereby permitting the grate bars to become heated from the hot fuel bed just above. The clinker then melts down into the spaces between the bars and the sulphur seems to combine with the iron of the grate. The heat warps the grate bars, and the clinker has such corrosive action on the hot iron that a set of grate bars is destroyed in the course of a few days. When such clinkering occurs, any attempt to slice the fire fails, and only slow and very difficult cleaning of the fires will remove the clinkers. Ordinarily, with coals forming loose clinkers, the cleaning of the fires took from seven to twelve minutes.

Virginia No. 4, West Virginia Nos. 14 and 15, and most of the Kansas coals clinker badly because the ash is low in proportion to the sulphur content—0.3 to 6 per cent of sulphur and 3.5 to 10 per cent of ash. When such coals are burned on a plain or a rocking grate trouble with clinkers may generally be prevented by blowing steam under the grate. The usually assigned cause of this effect is that as the steam passes through the hot clinkers it is decomposed into hydrogen and oxygen. This decomposition is a cooling process and the heat needed to effect it is taken from the grate and the hot clinker, thus keeping the latter cool and preventing the fusing of the clinker into the grate.

The use of steam to prevent the clinkers from melting into the grate was found to work satisfactorily with all the coals high in sulphur and ash. However, for coals very low in ash this method sometimes proved to be insufficient. In such cases crushed limestone spread over the thin, clean fire bed immediately on starting the test, prevented the clinkers from adhering to the grate, and was used for the second tests on West Virginia No. 14 and Virginia No. 4 coals. The cleaning of the fires after the first tests on these coals, when limestone was not used, took forty-five and thirty minutes, respectively. On the second tests, when limestone was used, the cleaning took eight and ten minutes, respectively.

To make a general statement, it may be loosely said that the tendency of a coal to clinker varies directly with the sulphur (iron pyrites) and inversely with the ash in the coal.

The statements of this paragraph regarding the effect of sulphur are at slight variance with those on page 34.

The curves of fig. 26 are based on 286 reliable tests, classified according to each of the two items, per cent of ash (ultimate analysis) in dry coal and over-all efficiency (item 73), the latter being the ratio of the heat put into the water to the potential heat in the coal put on the grate. Examination of the upper curve shows that the ash affects the efficiency by only 2 or 3 per cent until the ash content rises above 20 per cent, when the efficiency falls rapidly; however, not so many tests are represented in the last two points of the curve as in the others.

The lower curve shows the same fact inversely—that is, the high-efficiency tests are on coals low in ash. It indicates that an ash increase of 1 per cent causes a drop in efficiency of about 2 per cent, whereas the upper curve indicates a general drop of about 0.5 per cent in efficiency for each per cent of ash, or only one-fourth as much. The average, then, is about 1 per cent decrease in efficiency for 1 per cent increase in ash. The five points at the left end of the lower curve contain tests on clean lignites, and are therefore really not comparable with the other points. These five tests are individually given in the subjoined table.

The two curves show that ash is undesirable; but even so, the commercial choice of coals, so far as ash is concerned, is more a question of market price, freight rates, labor costs, and storage capacity, and of whether or not the present boiler plant is crowded.

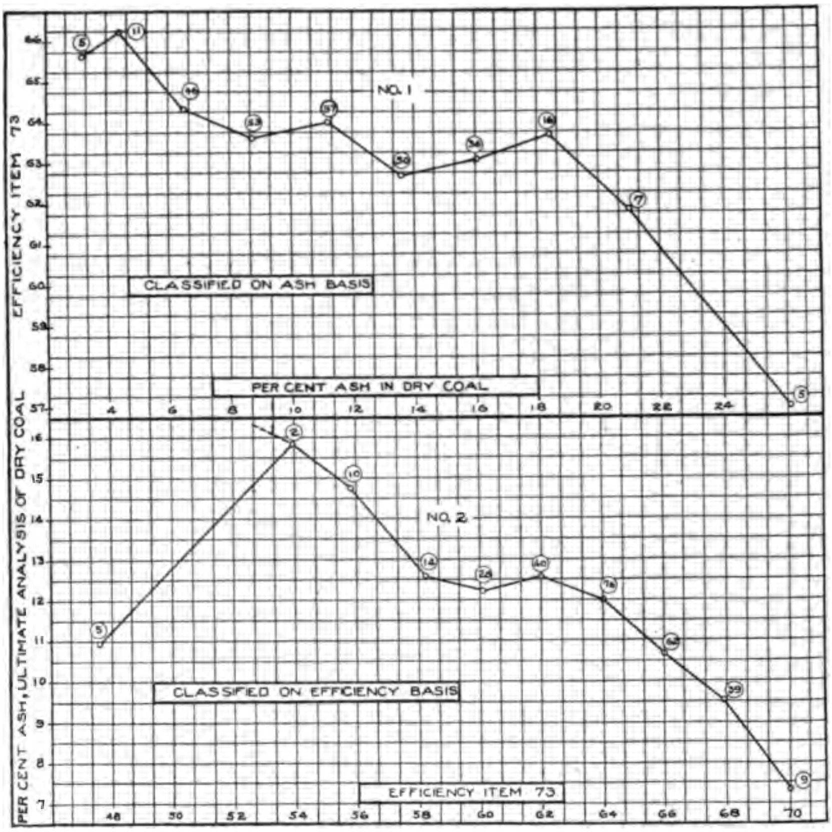


FIG. 26.—Relation of per cent of ash (ultimate analysis) in dry coal to efficiency 73, classified on each as a basis; tests 120–410.

Coals classed in first group of classification on basis of over-all efficiency (item 73).

Test No.	Coal.	Efficiency 73.	Per cent of ash (ultimate analysis) in dry coal.
303	Texas No. 4	49.00	12.95
298	.....do	51.16	12.86
401	Rhode Island No. 1	40.91	16.87
400	Wyoming No. 6	52.74	5.55
402	Utah No. 2	44.18	6.48

The table which follows shows that size has no evident influence on clinkering, which is the same finding as stated under "Classification on basis of average diameter of coal" (p. 47). These two tables are the converse of each other.

Classification of average diameter of coal on basis of per cent of clinker in refuse.

	Per cent of clinker.										
	Up to 10.	10 to 20.	20 to 25.	25 to 30.	30 to 35.	35 to 40.	40 to 45.	45 to 50.	50 to 55.	55 to 60.	Over 60.
Number of tests	15	4	4	6	14	13	46	43	53	42	28
Average per cent of clinker in refuse	0	13	23	28	33	37	42	47	52	57	62
Average of average diameter of coal, inches.	0.89	0.83	0.50	0.60	0.89	0.85	0.76	0.78	0.83	0.82	1.20

The curves of fig. 27 are plotted from the results of about 300 tests, and differ from those of fig. 26 in being based on the per cent of ash in coal as fired instead of in dry coal. Thus the ash is always less than in the dry-coal percentage, but by varying amounts, which perhaps explains the greater irregularity of the code "boiler-efficiency" line (72*), compared with the analogous line of fig. 26, based on over-all

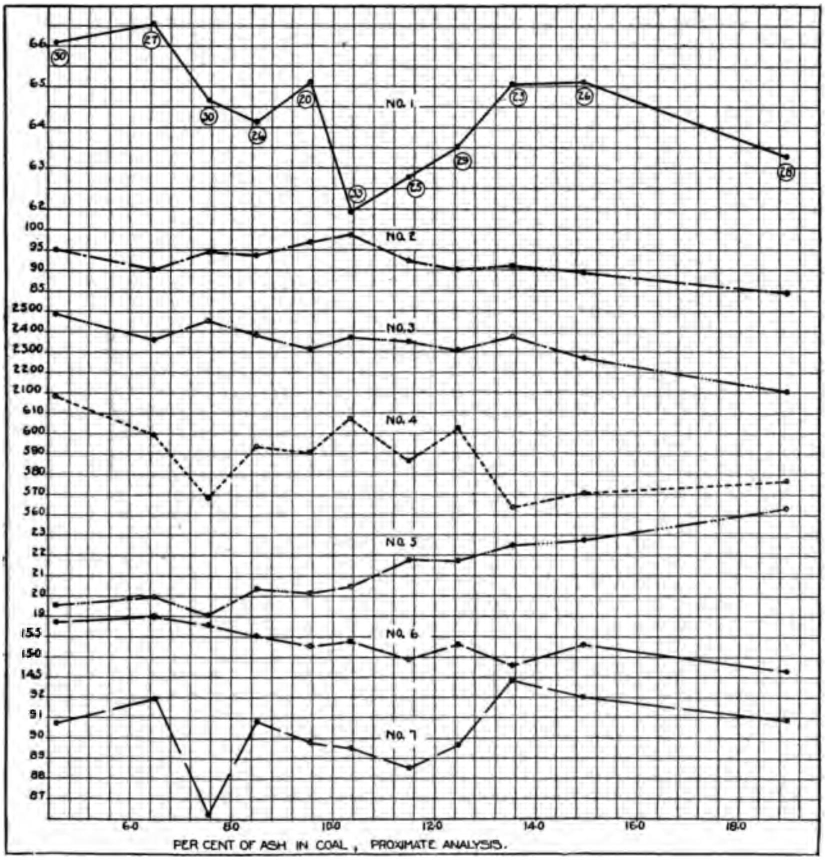


FIG. 27.—Relations of per cent of ash in coal (proximate analysis) to: Efficiency 72* (curve No. 1); per cent of rated capacity developed (curve No. 2); combustion-chamber temperatures (°F.) (curve No. 3); flue-gas temperature (°F.) (curve No. 4); pounds of dry chimney gases per pound of "combustible" (curve No. 5); carbon-hydrogen ratio in dry coal (curve No. 6); and per cent of completeness of combustion (E_3) (curve No. 7). Tests 89–401.

efficiency (code item 73). The tendency of the 72* line to fall is apparent.

A glance at curve No. 2 shows that ash has a worse effect on amount of steam generated, the decrease of which is considerable, than on efficiency.

Curve No. 3, combustion-chamber temperature, shows a steady drop of a few hundred degrees due to increasingly poorer fuel-bed conditions along with falling rates of steam generation.

Curve No. 4, flue-gas temperature, shows a slight drop on account of lower furnace temperatures.

Curve No. 5, the pounds of dry chimney gases per pound of "combustible," shows a marked and steady rise which is the chief reason for the decreasing-furnace and flue-gas temperatures just referred to. It is usually hard to keep the fuel bed in good condition when a coal is high in ash.

Curve No. 6 gives the averages for each group of the ratios of the carbon to the total hydrogen in the dry coal. This line drops, showing that the coals become poorer. The coals in the left-hand groups contain less oxygen in their molecules, so that their hydrogen, though decreasing in percentage, is available in larger amount. The fact that on going to the right the carbon-hydrogen ratio decreases partly accounts for the falling efficiencies shown by curve No. 1. (See p. 68.)

Curve No. 7, per cent of completeness of combustion[a] (E_3), indicates approximately the percentage of total heat liberated from the coal which ascended from the grate. It rises decidedly toward the right in spite of the poorer fuel-bed conditions. The explanation is that inasmuch as the furnace temperature was almost always above the ignition temperatures of all the combustible gases and smoke particles present combustion was retarded more on the left than on the right, because less oxygen was present. For this reason more of the possible heat was generated with the higher ash coals.

It is worthy of note that the high and low efficiencies (72*) in each group (values not shown here) do not vary much between groups. Commercially this similarity of highest efficiencies means that buying coal on the basis of per cent of ash shown by proximate analysis of coal as fired is an uncertain matter so far as obtaining high efficiency thereby is concerned. Classification of the tests made on Illinois, Indiana, and western Kentucky coals on an ash basis shows no more than the minor importance of ash above mentioned.

In making tests on sized coal, as given on pages 45 to 48, there would be an opportunity for research on the question of per cent of ash as affecting the results of boiler trials. Coals of the same size could be classified on the basis of per cent of ash and the effect of the ash thus studied separately from the effect of size. It does not seem, however, that for the range of per cent of ash found in coal this investigation would be important, for it is not the amount of ash, but its composition and distribution, that affects the results of a steaming test.

---

[a] See glossary (p. 181), under "Efficiencies."

With a knowledge of ash composition it could be decided how the coal was to be burned. For instance, a coal which did not clinker badly, but which burned leaving free ash, would be burned under ideal conditions on a rocking grate no matter how high the per cent of ash. A coal which clinkered badly at high temperatures should be gasified at a low temperature, thereby avoiding an amount of clinkering that would stop up the air passages and also preventing clinkers from adhering to the grate. It is a study of ash composition along with the manner of distribution of the ash in the coal that is needed.

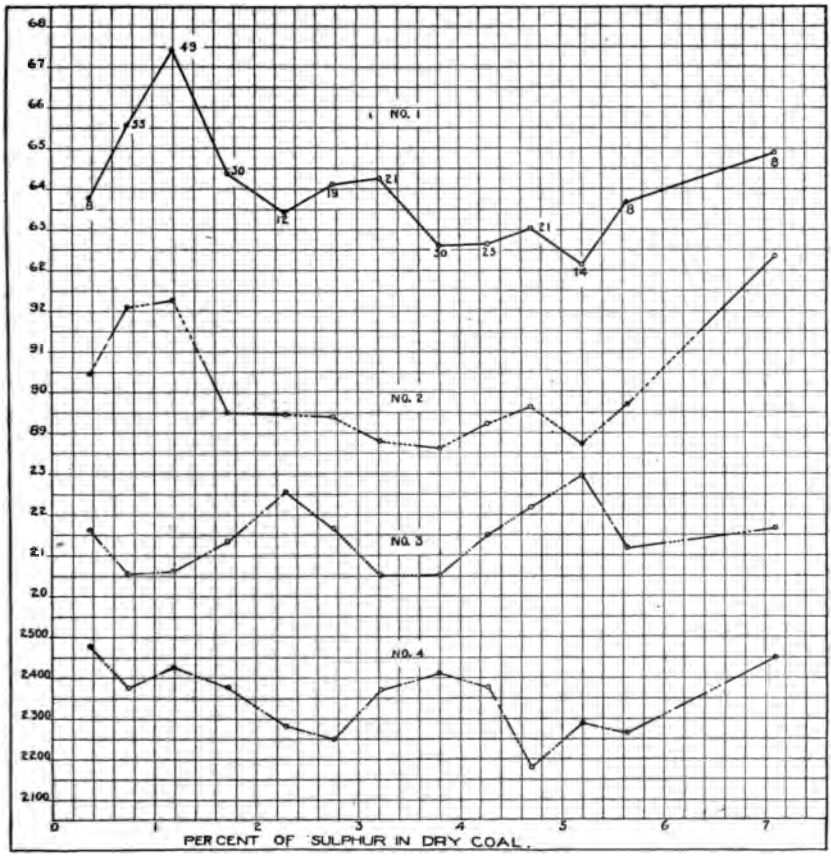


FIG. 28.—Relations of per cent of sulphur in coal to boiler efficiency 72* (curve No. 1); per cent of completeness of combustion (E_3) (curve No. 2); pounds of dry chimney gases per pound of "combustible" (curve No. 3); and combustion-chamber temperature (°F.) (curve No. 4) Tests 89–400.

The curves of fig. 28 present a classification based on per cent of sulphur in dry coal. For the low sulphur values there is a wide variation in efficiency 72*. As the per cent of sulphur increases, up to 5 per cent, there is a gradual drop in efficiency 72*. There were 16 tests in which the per cent of sulphur was over 5.4. At the high values of sulphur the efficiency 72* curve rises, probably because the sulphur is in different form and also differently distributed. A curve through the average efficiency points shows a drop of 5 per cent, with an increase of 5 per cent in the sulphur, or, in other words, every increase in the per cent of sulphur in dry coal decreases the efficiency in equal amount.

Curve No. 2 shows the per cent of completeness of combustion (E_3), and is nearly parallel to the efficiency 72* curve.

Curve No. 3 shows the pounds of dry chimney gases per pound of "combustible," and rises slightly with the per cent of sulphur.

Curve No. 4 shows the combustion-chamber temperature, which, except for the high sulphur values, decreases as the per cent of sulphur increases, indicating a value at the high sulphur values about 300° F. higher than an average curve through the combustion-chamber temperature points would indicate that it should be. The curves of fig. 17 (p. 25) show that this increase of temperature nearly accounts for the increase of efficiency 72* at the high sulphur values.

The curves of fig. 21 (p. 30) show that as the per cent of clinker in the refuse increases the per cent of sulphur increases; also that all the highest values for per cent of clinker are grouped with the higher values for per cent of sulphur. The low per cent of values for sulphur are grouped with the high values for per cent of efficiency 72*, and vice versa. At the highest values for per cent of clinker the efficiency 72* is lowest, and with high efficiency 72* the per cent of clinker is the lowest. This relation was determined from two different classifications—one on per cent of clinker in refuse and one on efficiency 72*. The classification on per cent of clinker in refuse shows that efficiency 72* is more influenced by per cent of clinker than the per cent of clinker is influenced by this efficiency. The latter influence was determined by classifying on an efficiency 72* basis.

On referring to fig. 24 (p. 36), a classification on the basis of per cent of clinker in refuse, it is to be noted that for all values of per cent of clinker the combustion-chamber temperature and pounds of dry chimney gases are about constant.

The general conclusion is that the per cent of sulphur does affect efficiency 72* indirectly by the formation of clinker. Since the amount of air used is a constant value, it is quite possible that the decreasing value of efficiency 72* with increasing per cent of sulphur is due to the effect of clinker on the distribution of the air supply. Moreover, with the high values for per cent of clinker probably more of the air enters the furnace over the fire.

AVERAGE DIAMETER OF COAL.

Preliminary to the discussion of the results produced by using coal of different sizes it may be of value to state how the coal is received at the fuel-testing plant and how the size is determined, and to suggest how further research work might be done on the influence of size.

Nearly all of the coal tested was passed through a crusher, and consequently coals of widely varying characteristics were reduced to the same size. Therefore by classifying coals on a size basis, as we have done, we have averaged a good eastern coal with a poor-grade western coal. While size shows, on the average, some few general relations, it would seem that the best comparable data could be obtained by taking one coal, say, run of mine, and after separating the various sizes, making a series of tests on each size. Even such tests would not be made on the same grade of coal, as the smaller sizes are sure to be higher in ash; but nevertheless this side of the problem is of commercial importance.

After the sample of the coal tested has been quartered and a part sent to the chemist for analysis, the remainder is passed through a revolving screen perforated its entire length with round holes ranging from one-eighth to 1 inch in diameter. These holes are arranged in strips or sets of rows, the width of which decreases as the size of hole increases. The coal passing through each set of holes is weighed separately and the data from the boiler room are reported, as follows:

Determination of average diameter of coal samples.

Diameter of holes (inches).	Pounds of coal through each set of holes.		Weight of coal determining average size.
	Actual.	Reduced to 100-pound basis.	
1.	2.	3.	4.
$\frac{1}{8}$	20	20.4	2.6
$\frac{1}{4}$	14	14.3	3.6
$\frac{3}{8}$	18	18.4	6.9
$\frac{1}{2}$	12	12.2	6.1
$\frac{3}{4}$	27	27.6	20.7
1	4	4.1	4.1
$1\frac{1}{2}$	3	3.0	4.5
	98	100.0	$\frac{48.5}{100.0}=0.49$

Column 2 shows that 98 pounds of coal was sized. No attempt is ever made to weigh out exactly 100 pounds, so the weights must be reduced to 100, as has been done in column 3, thereby obtaining the percentages of the various sizes of coal. From the construction of the revolving screen it follows that in an average diameter each of the percentages has a "weight of observation" proportional to the diameter which it represents. In getting average diameter, then, column 3 is multiplied by column 1, obtaining column 4, and the sum of this column of products divided by 100, therefore, gives the weighted average size of the coal.

The classification plotted in the curves of fig. 29 was made on the coals tested in tests 89 to 401, and shows that as the average diameter increased from 0.35 to 1.26 inches (1) the capacity increased about 15 per cent (curve No. 3); (2) the highest efficiency 72* values were obtained with the smallest sizes (curve No. 5); (3) there was practically no change in the per cent of completeness of combustion (curve No. 6); (4) there was a slight decrease in the pounds of dry chimney gases per pound of "combustible" (curve No. 4); and (5) the carbon-hydrogen ratio figured from the dry coal decreased considerably (curve No. 7), showing that the good coals fall in the groups of small-

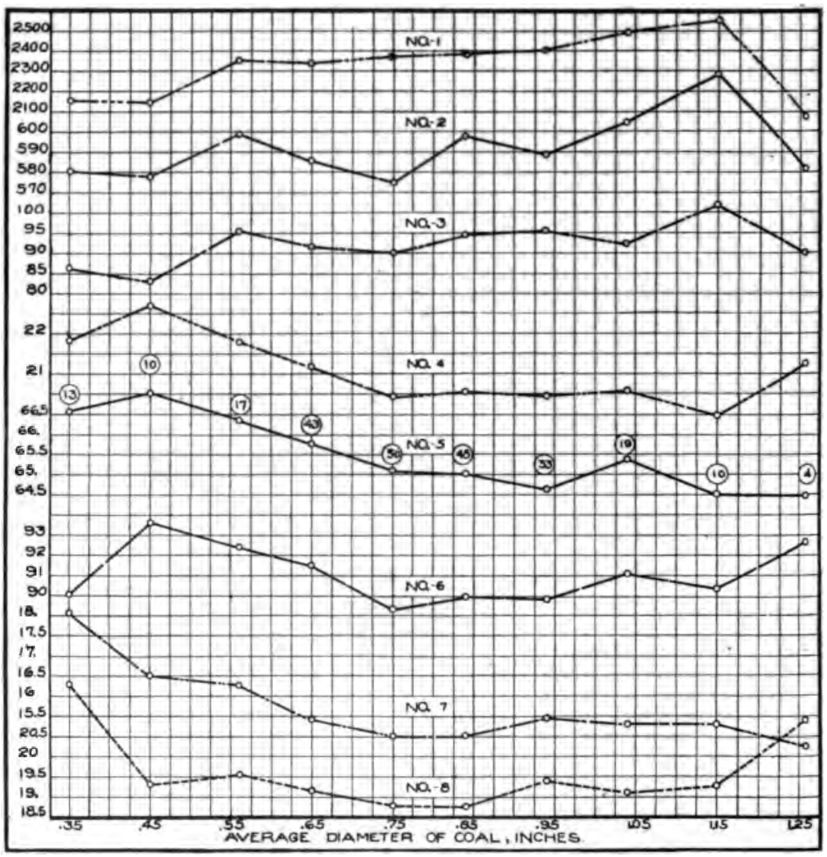


FIG. 29.—Relations of size of coal to combustion-chamber temperature (°F.) (curve No. 1); flue-gas temperature (°F.) (curve No. 2); per cent of rated capacity developed (curve No. 3); pounds of dry chimney gases per pound of "combustible" (curve No. 4); efficiency 72* (curve No. 5); per cent of completeness of combustion (E_3) (curve No. 6); carbon-hydrogen ratio in dry coal (curve No. 7); and ratio of carbon to available hydrogen (curve No. 8). Tests 89–401.

est average diameter, this result being probably due to the fact that some of the good coals broke up badly in transportation and in passing through the crusher; (6) the combustion-chamber temperature increased about 400° F. (curve No. 1).

It should be borne in mind in considering these general results, which are so different from the usual conclusions, that they are only tentative, because other conditions varied so widely. The study of effect of size as above outlined is not specialized enough, for undoubtedly other factors than average size are influential—e. g., perhaps, percentage of voids, as dependent on percentage of various sizes forming average diameter, shape of pieces, etc.

In discussing the effect of average size of coal as based on these tests it is well to remember that none of the coal is really fine, for the lowest sizes averaged about 0.3 inch. On the other hand, the largest sizes averaged only 1.25 inches.

The tabulation headed "Classification of per cent of clinker on basis of average diameter of coal," which follows, was made to ascertain whether the size of coal had any influence on its tendency to clinker. About 300 tests were used, but they were on all kinds of coal, from all parts of the country, and no such influence is indicated. (See "Classification on basis of per cent of clinker in refuse," p. 41.)

Classification of per cent of clinker in refuse on basis of average diameter of coal.

	Average diameter (inches).									
	Below 0.40.	0.40 to 0.50.	0.50 to 0.60.	0.60 to 0.70.	0.70 to 0.80.	0.80 to 0.90.	0.90 to 1.00.	1.00 to 1.10.	1.10 to 1.20.	Over 1.20.
Number of tests	15	16	19	41	51	45	33	19	8	21
Average diameter of coal (inches)	0.35	0.44	0.56	0.65	0.75	0.84	0.94	1.04	1.14	1.25
Average per cent of clinker in refuse	44	46	35	43	46	47	50	46	34	45

Fig. 30 shows some of the many variations encountered when making sizing tests. The seven tests from which this chart was plotted were made on mixed bituminous coals, made up of several of the officially numbered coals, and accurately sized by passing through a revolving screen. The per cent of sulphur and per cent of moisture were about constant in the mixtures. The fact that the carbon-hydrogen ratio of the dry coal used decreased as the coal became larger (curve No. 1) seems to indicate that the tests were not run on uniform mixtures of coals; perhaps certain coals were finer or coarser than others before mixing. The coals were accidentally mixed in a general heap, in consequence of a fire in the washer plant, and it was not known just what they consisted of except that they came from the so-called Illinois and Missouri coal basins.

A significant fact brought out by the chart is that the efficiency 72* was about constant for all the sizes.

Certain values varied as the size of the coal increased. Curve No. 1 shows that the carbon-hydrogen ratio in dry coal decreased, and thereby tended to lower efficiency 72*. Curve No. 2 shows a slight rise of efficiency 72*. Curve No. 3 shows a steady increase in the difference between the draft in the stack and that over the fire, for which no explanation is offered. Curve No. 4 shows an irregular but decided increase in pounds of coal burned per square foot of grate per hour—a direct consequence of the increase in size of the coal. It should be borne in mind that the stack draft available was always about the same. Curve No. 5 is of the same shape in detail as No. 4, and shows an increase in the rate of steam production. Curve No. 6 is practically level, except at the left end, where it is high—perhaps because the coal was so fine that it caked and allowed cracks to form in the

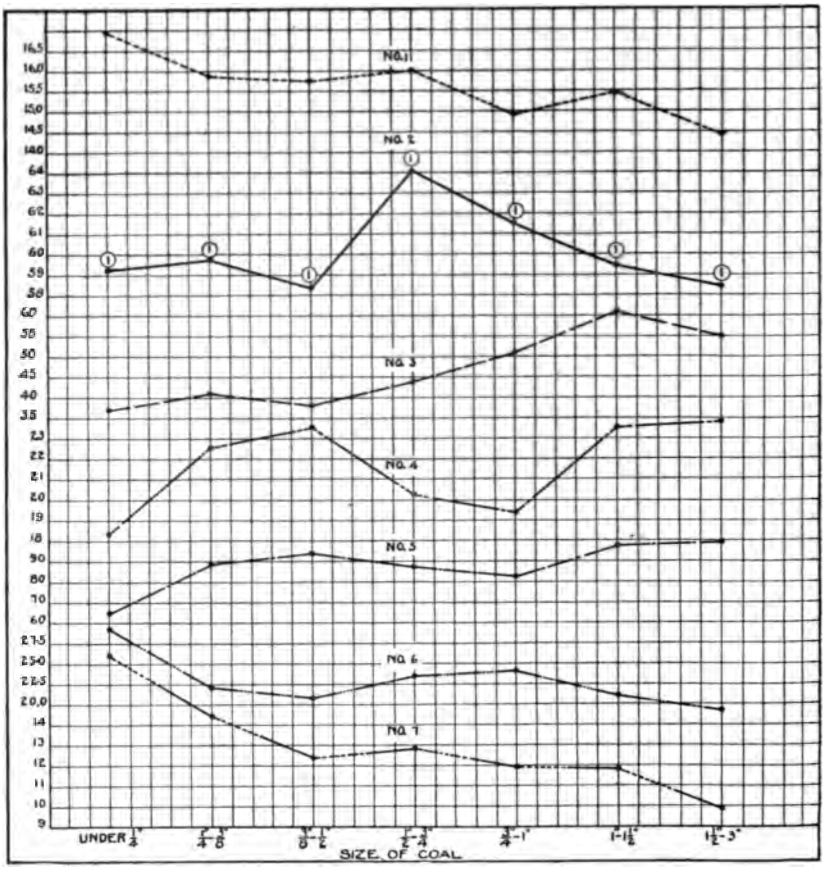


FIG. 30.—Relations developed on accurately sizing mixed bituminous coal: Curve No. 1, carbon-hydrogen ratio in dry coal; No. 2, efficiency 72*; No. 3, difference between draft in stack and draft over fire; No. 4, pounds of dry coal burned per square foot of grate surface per hour; No. 5, per cent of rated capacity developed; No. 6, pounds of dry chimney gases per pound of "combustible;" No. 7, per cent of ash in coal (proximate analysis).

fuel bed, or because the ash contained was high. Curve No. 7 shows that much of the ash went into the fine coal. It is worthy of remark that the finer and dirtier sizes gave nearly as high efficiency as the larger sizes.

The sole advantage of the larger sizes of coal over the smaller, so far as shown by these few tests, was that a higher rate of steam production was attained.

An attempt was made to determine the effect of ⅛-inch size (in Indiana, Illinois, and western Kentucky coals) on efficiency 72*, per cent of CO loss, and combustion-chamber temperature; but the results were negative, and emphasize the statements made on page 47, that the study of the effects of the various elements of size of coal has not been made in sufficient detail. It is also likely that the effects of size are obscured greatly by other factors, such as caking, moisture, etc. The following table of results does not seem to indicate much:

Classification of efficiency 72, per cent of CO in flue gas, and combustion-chamber temperature on basis of per cent of ⅛-inch coal (Illinois, Indiana, and western Kentucky coals).*

	Per cent of ⅛-inch coal.						
	0 to 5.	5 to 10.	10 to 12.	12 to 14.	14 to 16.	16 to 17.	17 to 18.
Number of tests[a]	4	13	9	4	4	7	7
Average per cent of ⅛-inch coal	4.0	8.2	11.1	12.2	14.9	16.2	17.6
Average efficiency 72*	65.02	63.74	66.18	68.05	65.57	65.88	63.88
Average per cent of CO in flue gas	0.11	0.27	0.19	0.19	0.30	0.18	0.17
Number of tests[a]	3	8	7	3	2	6	2
Average combustion-chamber temperature (° F.)	2,612	2,483	2,367	2,302	2,240	2,370	2,393

	Per cent of ⅛-inch coal.					
	18 to 19.	19 to 21.	21 to 23.	23 to 25.	25 to 30.	30 to 40.
Number of tests[a]	4	9	6	6	6	5
Average per cent of ⅛-inch coal	18.4	19.9	22.0	24.0	26.2	32.7
Average efficiency 72*	66.74	64.98	65.84	65.92	66.67	65.84
Average per cent of CO in flue gas	0.24	0.26	0.16	0.13	0.14	0.27
Number of tests[a]	2	4	3	5	4	4
Average combustion-chamber temperature (° F.)	2,371	2,299	2,104	2,245	2,245	2,378

[a] Fewer tests were used to obtain the average combustion-chamber temperature than for the other averages, owing to the fact that the questionable results were eliminated.

The coals used for sizing came from Illinois, Indiana, and western Kentucky. Not many tests are used here and the results would not be expected to convey much information even had the coals come from one locality; because, for example, from the State of Illinois it is possible to obtain about as good and as poor bituminous coal as is mined. The results, given in the table on the following page, show a small increase in efficiency 72* and a large increase in combustion-chamber temperature as the size of coal increases.

Classification of efficiency 72, per cent of CO in flue gas, and combustion-chamber temperature on basis of average diameter of coal (Illinois, Indiana, and western Kentucky coals).*

	Average diameter (inches).							
	Up to 0.5.	0.5 to 0.6.	0.6 to 0.7.	0.7 to 0.8.	0.8 to 0.9.	0.9 to 1.0.	1.0 to 1.2.	1.2 up.
Number of tests[a]	9	4	16	22	15	7	3	8
Averages of average diameter (inches)	0.39	0.58	0.66	0.74	0.83	0.95	1.04	2.51
Average efficiency 72*	64.83	67.69	65.75	65.19	65.00	66.88	68.50	63.68
Average per cent of CO in flue gas	0.18	0.31	0.16	0.23	0.20	0.34	0.15	0.11
Number of tests[a]	7	2	7	14	11	5	3	4
Average combustion-chamber temperature (° F.)	2,080	2,406	2,258	2,357	2,405	2,412	2,542	2,576

[a] Fewer tests were used to obtain the average combustion-chamber temperature than for the other averages, owing to the fact that the questionable results were eliminated.

Increasing the size of fuel by briquetting would seem from theoretical reasoning to be a move in the wrong direction. Other things being equal, it is self-evident that the more nearly the size of a particle of coal approaches that of an atom the better, for then each particle will burn instantly on coming in contact with two atoms of oxygen. It is also self-evident that the smaller the individual particles of coal put into a furnace or gas producer the less will be the protecting effect of the surface coating of ash formed by the burning away of the outer portions of the grains. From a mathematical standpoint it can be seen that the volume of a body increases proportionately to the cube of its diameter, but the exposed surface increases only as the square of its diameter, and in combustion it is exposed surface that counts for rapidity. Therefore, to repeat, it would seem that on this basis alone, artificially increasing the size of fuels is, to speak generally, working in the wrong direction. It is recognized that improved results are obtained by briquetting some fuels, but that probably still better results can and will be obtained in the future by devising furnaces and gas producers of such types as will utilize fine coal better than coarse. So far the only step made in this direction has been the burning of pulverized coal in furnaces. Perhaps the slowness of development in this field is attributable to the expense of grinding the coal, which has never had a fair trial on a large scale, and also indirectly to the softening of the fire-brick lining due to the fact that pulverized-coal furnaces are customarily run too hot. The work done by the boiler division, and set forth on pages 20, 23, 56, shows the error of the general impression that very high furnace temperatures are necessary for very high over-all efficiencies. Viewed from this standpoint, it is not improbable that in the future the burning of fine and pulverized coal, perhaps even without extreme pulverization, will increase largely. In cement kilns, for instance, such coal has been a great success for the reason that the lining of the kiln is protected by the material itself which it is desired to melt. One reason for the nonutilization of slack coal is because too little attention has been given to this general subject.

As indicating a right trend in this matter, attention may be called to the success of the large power houses of the country in burning fine coals, which a few years ago were used as railroad ballast or thrown on dump heaps. The over-all efficiencies are in many cases quite equal to those which could have been obtained with the stokers and grates of a few years ago when using cleaner coals of larger and more uniform size. Perhaps in a few more years no complaint will be heard against fine coal. Every engineer knows that, whereas egg and lump coal used to be sought after, the large power houses now put all their coal through crushers which reduce it to a size which a few years ago would have been thought almost useless.

PER CENT OF RATED CAPACITY DEVELOPED.

No attempt is made here to discuss in detail the causes of the showing of the following table, which is one of the most significant in this volume. It indicates that for every capacity group the "boiler efficiency" (72*) is independent of the combustion-chamber temperature and practically constant throughout the whole range of temperature. The suggested explanation is that as the temperature of combustion rises the oxygen content of the gases decreases, which reduces the completeness of combustion sufficiently (see figs. 13, p. 22; 14, p. 23; and 31) to neutralize the slight rise of boiler efficiency due to higher initial temperatures. This same result is shown for all tests grouped with regard to amount of coal burned (figs. 12, p. 21; and 17, p. 25).

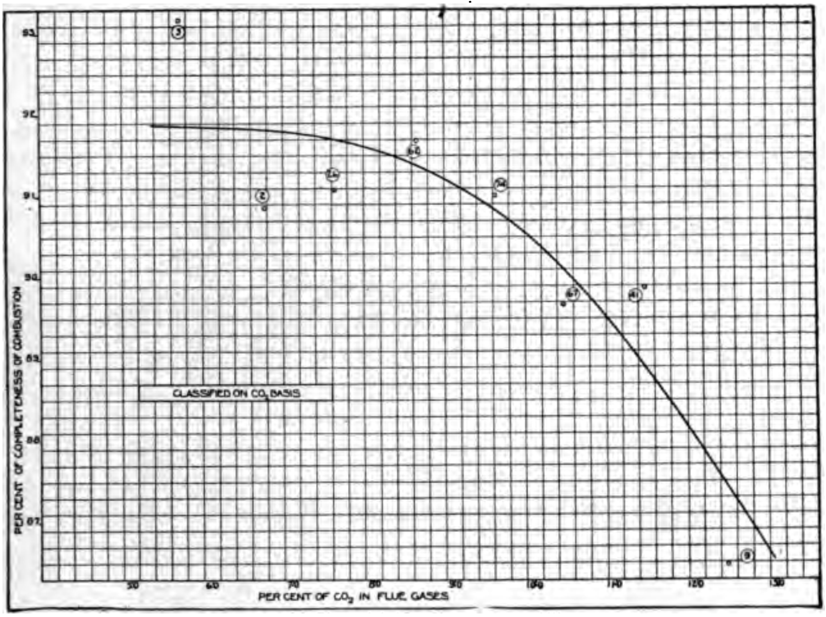


FIG. 31.—Relation of per cent of CO_2 in flue gases to per cent of completeness of combustion (E_3), tests 89–401.

Classification of combustion-chamber temperature and efficiency 72 on basis of per cent of rated capacity developed.*

Per cent of rated capacity developed.											
70 to 75.			75 to 80.			80 to 85.			85 to 90.		
Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.	Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.	Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.	Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.
1,870	1	66.38	1,880	1	60.89	1,961	1	67.64	2,067	6	65.93
1,936	2	64.07	1,967	2	59.79	2,046	4	62.33	2,140	2	64.56
2,253	1	65.04	2,039	3	66.35	2,163	3	67.68	2,231	9	66.13
			2,118	1	65.95	2,259	11	65.79	2,354	8	64.83
			2,247	1	68.54	2,325	5	67.39	2,421	5	65.79
			2,350	2	63.68	2,419	5	66.87	2,525	1	65.25
						2,597	1	66.82	2,672	2	65.94
		[a]64.89			[a]64.12			[a]66.06			[a]65.59

Per cent of rated capacity developed.											
90 to 95.			95 to 100.			100 to 105.			105 to 110.		
Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.	Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.	Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.	Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.
2,050	2	67.46	2,248	6	67.32	2,256	2	65.09	2,290	3	66.19
2,178	2	65.88	2,368	7	65.63	2,327	3	66.46	2,345	3	67.44
2,244	3	69.23	2.457	11	65.83	2,474	4	67.55	2,448	9	65.03
2,359	12	65.45	2.554	6	64.88	2,550	5	66.10	2,534	1	65.83
2,456	8	65.88	2,627	2	65.80	2,660	1	65.22	2,653	5	65.01
2,546	5	69.41	2,722	1	68.06	2,839	2	66.55	2,708	1	64.61
2,637	1	68.61							2,864	1	73.64
2,708	1	64.97									
		[a]66.60			[a]65.95			[a]66.38			[a]65.88

[a] Average.

PYROMETRY.

For measuring the furnace and the combustion-chamber temperatures, both a Wanner optical pyrometer and a thermoelectric couple of platinum and platinum rhodium were used.

The Wanner optical pyrometer (fig. 10, p. 19) was the more reliable and by far the more convenient to use. The working of this instrument is based on the relation which exists between the temperature of a hot body and the intensity of the light which it emits.[a] The instrument itself makes use of an incandescent lamp which is standardized by comparison with an amyl-acetate standard lamp, and consists of a photometer for comparing the light emitted by the body whose temperature is to be measured with a steady light of known intensity. The comparison light is a 6-volt incandescent lamp, supplied by a storage battery, illuminating a ground-glass surface. A beam of monochromatic (red) light from this source—produced by means of a direct-vision spectroscope and a screen, cutting out all but a narrow band in the red—and a similar beam from the hot body are passed into a photometric telescope, each beam illuminating one-half of the telescopic field. The photometric comparison is made by adjusting to equal brightness both halves of the telescopic field by means of a polarizing arrangement.

---

[a] For the theoretical discussion of this subject see Waidner, C. W., and Burgess, G. K., Optical pyrometry: Bull. No. 2, Bureau of Standards, U. S. Dept. Commerce and Labor.

One of the advantages of the optical pyrometer is that it is more apt to take the average temperature of a strip across the furnace from wall to wall. Furthermore, it gives temperature changes instantaneously and in absolute measure, which, even in case the flames appear hotter than they really are, can hardly be in error more than 150° F. This error is probably more than offset by the fact that the furnace is not a perfect "black body."

The most serious source of error, except when special precautions are taken, is the variation in brightness of the electric comparison lamp due to variation in the current furnished by the three-cell storage battery, the percentage of change in light being of the order of six times the percentage of change in current through the lamp. Breaking the circuit and then making it again may cause an apparent change of more than 20° C. It has been found that for a series of observations lasting from one-half hour to two hours it is better to take all readings, after once standardizing the instrument, without breaking the lamp circuit, instead of breaking it after every single reading.

Before standardizing the instrument the amyl-acetate standard lamp should be allowed to burn from five to ten minutes to get a steady flame. To supply the incandescent lamp a 20-ampere-hour storage battery was used for most of the readings recorded in this work.

The thermoelectric couple used for pyrometric tests was connected either to a millivoltmeter equipped with a scale of temperatures or to a Callendar recording instrument. There were two of the latter instruments; one was to be used with the thermoelectric-couple pyrometer and the other with an electric-resistance pyrometer. Owing to the fact that these pyrometers, as sold, do not stand the furnace temperatures for any great length of time there was no opportunity to give the recording instruments a fair trial, and therefore they are not considered in detail in this report.

The thermoelectric couple as it came from the maker consisted of a platinum and platinum-rhodium junction inclosed in a porcelain tube of ⅜-inch bore and ⅝-inch outside diameter. However, this porcelain tube could not stand the high temperature, and particularly the slagging action of the furnace gases. The slag accumulated on the surface of the tube and seemed to change the composition of the porcelain. The tube partly melted, and then, after it had been in the combustion chamber for two hours, broke off, although there was nothing in the chamber to strike it. A water-jacketed iron pipe, similar to the gas sampler shown in fig. 15 (p. 24), was tried instead of the porcelain tube, the two wires being insulated from each other and from the pipe by pieces of small glass tubing. The thermoelectric junction projected 3 inches from the end of the iron pipe, and was held in two stems of penny clay pipes. This arrangement lasted over a week in the combustion chamber and gave fairly satisfactory results. During this time the couple was continually connected to the Callendar recording instrument.

The records obtained with the thermoelectric apparatus had a value only so far as the relative temperatures were concerned. For absolute temperature the apparatus could not be depended on, because it was impossible to apply any scale or rule to the record when the mass around the junction of the couple was one fused mass of slag. It was also found that the variations in temperature shown by this couple were lagging from six to eight minutes. A couple fitted with a water-jacketed iron pipe had to be rigidly connected to a water supply. On that account such an arrangement could not be used for measuring temperatures in different parts of the furnace, and for this purpose a plain ½-inch iron pipe was used. The junction of the wires was, as before, held in two clay pipestems, which projected about 2 inches from the end of the iron pipe. Clay pipestems had to be used also for insulating the wires inside of the iron pipe for a length of about a foot back from the end, on account of the high temperature to which the end was subjected. Even with this special arrangement the thermoelectric couple could be exposed to the high temperature of the furnace only long enough to get the projecting junction hot and take the reading. This exposure usually lasted fifteen to twenty seconds, after which the instrument had to be withdrawn and cooled off. Even with this care the iron pipe lasted for only thirty to fifty single readings, after which it became so burned that it had to be replaced by a new one. This instrument also could be depended on only for relative temperatures in different parts of the furnace.

After all the difficulties that are encountered in using a thermoelectric couple for measuring furnace temperatures, this apparatus measures only the temperature of a very small part of the furnace, where the instrument is inserted, and the temperature midway between the side walls may be much higher than it is at points reached by the couple, 8 inches from the walls.

Fig. 32 gives a comparison of the combustion-chamber temperatures taken with the Wanner optical pyrometer with the rise in temperature of water from a water-jacketed gas sampler inserted in the rear of the combustion chamber. A mercury thermometer was inserted into the water outlet of the gas sampler and was read simultaneously with the optical pyrometer. The two curves agree very well, the temperature of the water lagging slightly. The elevation of temperature at A, B, C in the water-temperature curve is due to reduction of pressure in the water main caused by the taking of water into the measuring tanks for feeding the boiler. But for this circumstance the curve would run as shown by the dotted lines A, D, C.

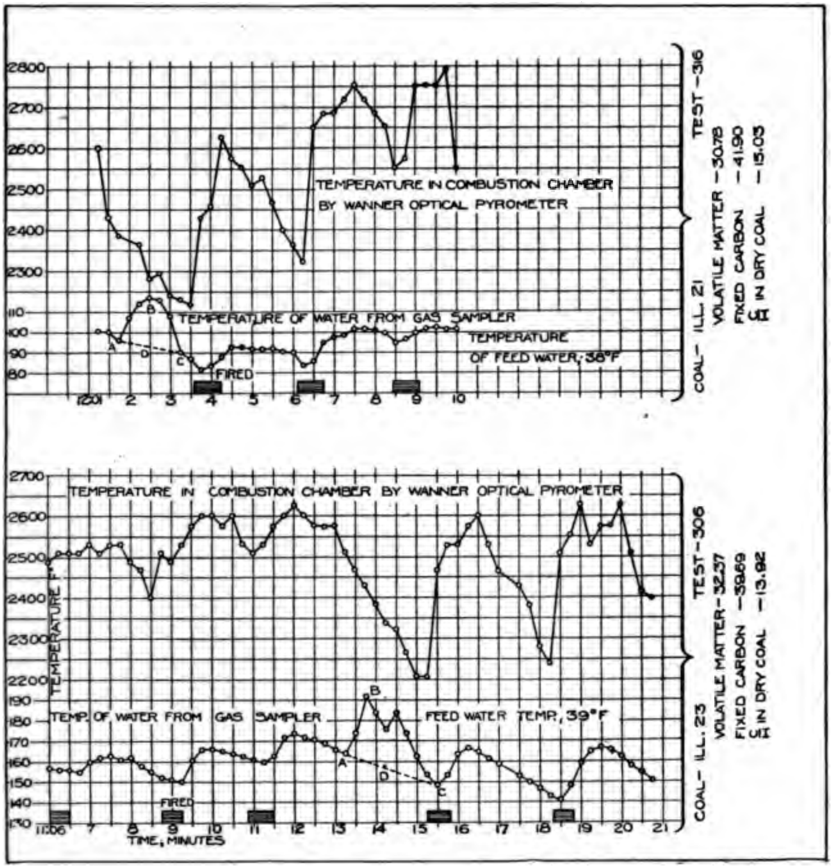


Fig. 32.—Comparison of Wanner optical pyrometer temperatures in combustion chamber with rise in temperature of water from a jacketed gas sampler.

SMOKE.

The curves of fig. 33 are plotted on the basis of per cent of black smoke. Curve No. 1 indicates that the efficiency 72* rises a little more than 1 per cent until about 20 per cent of black smoke is reached, and then gradually drops. This drop in efficiency amounts to about 2.5 per cent within the range of 20 to 50 per cent of black smoke. The drop in efficiency when there is little or no smoke can be explained by noting that a greater amount of air was used for combustion of the coals producing little smoke, probably owing to the fact that many lignites were included in these groups, the excess of air reducing the heat available for the boiler and causing a greater loss of heat up the stack. The loss up the stack decreases and the efficiency 72* rises with reduction in the supply of air until the point is reached at which the loss due to incomplete combustion becomes larger than

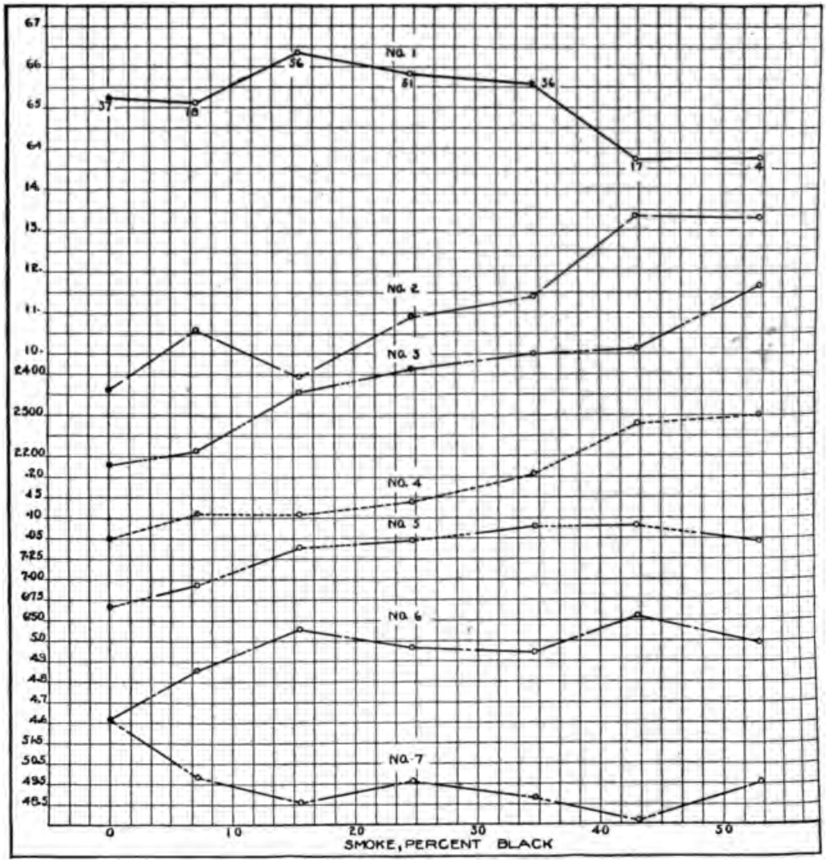


FIG. 33.—Relations of smoke per cent to boiler efficiency 72* (curve No. 1); per cent of unaccounted for loss taken from heat balance (curve No. 2); combustion-chamber temperature (°F.) (curve No. 3); per cent of CO in flue gases (curve No. 4); per cent of oxygen (ultimate analysis) in dry coal (curve No. 5); per cent of available hydrogen in "combustible" (curve No. 6); and per cent of fixed carbon (proximate analysis) (curve No. 7). Series of 1905–6; black smoke taken as 100 per cent.

the gain obtained by reducing the loss up the stack. Curves Nos. 3 and 4 support this explanation.

Curve No. 3 shows that the combustion-chamber temperature rises in direct proportion with the per cent of black smoke. Rise in combustion-chamber temperature always indicates a decrease in air supply.

Curve No. 4 shows a gradual increase in CO in the flue gases. The unaccounted-for loss, represented by curve No. 2, also rises as the smoke increases. It is reasonable to say that the greater part of the increase in the unaccounted-for loss is due to incomplete combustion of hydrocarbon gases and to the escape of solid particles of carbon-forming smoke.

Curve No. 5 shows but a small increase in oxygen in coal, and therefore does not indicate that oxygen in coal is a direct cause of smoke.

Curves Nos. 6 and 7 indicate that, excepting the first point at the extreme left, good or bad coals have not been prevalent in any one group.

The direct cause of the smoke seems to be shown in curve No. 3, which indicates increased rate of combustion and decreased supply of air.

The table which follows indicates that eastern coals are about as apt to smoke as western. It should be stated here that if these coals had been handled as suggested below most of them would probably have burned entirely without smoke, and the remainder with less smoke than they produced as actually handled.

Average per cent of black smoke produced by burning coals from certain localities under a Heine boiler.

Locality.	Number of tests.	Average per cent of black smoke.	Locality.	Number of tests.	Average per cent of black smoke.
Alabama	8	10.2	North Dakota	1	0
Arkansas	6	0	Ohio	25	32.2
Brazil	2	0	Pennsylvania	18	18.3
Florida	1	54.8	Rhode Island	1	0
Illinois	35	18	Tennessee	29	14.6
Indiana	30	26	Texas	3	8.7
Kansas	2	22.7	Utah	3	2.8
Kentucky	4	18.5	Virginia	10	36.1
Maryland	3	5.2	Washington	4	19
Missouri	7	17	West Virginia	23	22.9
New Mexico	8	17.6	Wyoming	8	14.7

The following table includes coals from many localities; some of them are usually called "smoky coals." It is quite probable that most other coals which produced smoke could have been burned smokelessly if the boiler division had not worked for the greater part of 1905 under the idea that very high temperatures are needed to get good over-all efficiencies. As shown elsewhere, extremely high furnace temperatures and a high degree of completeness of combustion in the furnace are incompatible. More air should usually have been admitted through the smoke-preventer openings to the space over the fire; this precaution might have prevented almost wholly in most cases the formation of the smoke without affecting the over-all efficiency of the outfit.

Coals burned under Heine boiler without producing smoke.

	Test No.
Alabama No. 3	390
Alabama No. 4	378
Arkansas No. 7 A	293, 294
Arkansas No. 8 (washed)	308, 309
Arkansas No. 10	340
Brazil No. 1	172, 173
Illinois No. 6 B (briquets)	313
Illinois No. 11 C (briquets)	312
Illinois No. 20	292
Illinois No. 21	316
Illinois No. 21 (briquets)	318
Illinois No. 23 A (washed)	317
Illinois No. 25	338, 339
Indiana No. 7 B (briquets)	288
Maryland No. 1 (washed)	231
Missouri No. 5	320
New Mexico No. 3 B	389
North Dakota No. 3	206
Pennsylvania No. 8	236, 237
Pennsylvania No. 8 (dried)	242
Rhode Island No. 1	401
Tennessee No. 5	352
Tennessee No. 6	379, 381
Tennessee Nos. 8 A and 8 B (washed)	388
Tennessee No. 9 (washed, briquets)	393
Texas No. 4	291
West Virginia No. 19	285, 289
West Virginia No. 19 (briquets)	331
West Virginia No. 21	297
Wyoming No. 2 B	210
Wyoming No. 3	211

COMBUSTION AND COAL.

"VOLATILE MATTER," "FIXED CARBON," "WATER OF COMPOSITION,"[a] AND "COMBUSTIBLE."

There still lingers a trace of an old idea that coal consists of particles of carbon cemented together with a sort of natural bitumen. The present tendency is to regard bituminous coal as a mixture of dozens, or even hundreds, of organic compounds, most of them derived from cellulose and many of them containing nitrogen and sulphur organically combined. It is true that for most kinds of coal group formulas can be devised which represent very closely the chemical compositions of the respective groups as shown by ultimate analyses; but it must be distinctly borne in mind that the devisers of these formulas do not mean that any one coal under consideration consists of one compound expressed by the formula proposed. Such formulas are meant as collective only; in exactly the same way as physiologists speak of the normal or average man, whose height, weight, etc., bear certain accurate relations to each other, although there is not in the world any one man who fits the description exactly.

When coal is heated, some or most of its constituent compounds are always broken down more or less, but are broken down differently, according to the particulars of the distillation method. That portion which is distilled off from coal when it is heated under certain "standard" conditions is called "volatile matter." But inasmuch as the "standard" conditions are seldom exactly alike, and inasmuch as "volatile matter" is the product of a change, it is a mistake to say that coal contains any stated percentage of "volatile matter," or even that it contains "volatile matter" at all. The terms "fixed carbon," "volatile carbon," and "water of composition" are equally misleading. Coals do not literally contain these constituents in any more exact sense than cane sugar consists of "water" and "charcoal," although hydrogen and oxygen are contained in cane sugar in exactly such proportions as form water and leave carbon when the sugar is heated.

---

[a] For definition of "water of composition," see the glossary, p. 183.

GRATE AND COMBUSTION SPACE.

Any furnace consists of the grate and the combustion space. The combustion space extends from the top of the fuel bed to the opening into the tube chamber, and its rear portion is termed the "combustion chamber." The function of the grate and fuel bed is to distill the "volatile matter" and partly to burn the "fixed carbon" of the coal. The function of the combustion space is to burn the "volatile matter." With coals high in "fixed carbon" combustion is nearly complete a short distance from the top of the fuel bed; with highly volatile coals the combustion is incomplete, even at the rear of the combustion chamber.

Samples of furnace gas collected at the top of the fuel bed are very commonly rich in combustible ingredients In the subjoined table is given the chemical composition of gas collected at the top of the fuel bed and also from the combustion chamber, determined from samples collected with the water-jacketed sampler. The samplers projected about 10 inches into the furnace, both being inserted through holes in the side wall, the first sampler resting on the surface of the fuel bed.

Analyses of samples of gas collected at top of fuel bed and rear of combustion chamber.

Collections.	Time.	CO_2.	O_2.	CO.	H_2.	CH_4.	C_nH_{2n+2}.
Test 362:							
Top of fuel bed	8.40	6.1	0	17.9	7.8	3.6	0.2
	10.40	10.8	5.6	2.2	0	0	0
Rear of combustion chamber	8.30	11.4	7.7	0	....	....	....
	10.30	14.4	3.0	0	....	....	....
Test 364:							
Top of fuel bed	8.15	8.4	8.9	2	0	0	0
	12.30	5.7	0	20.3	0	2.7	0
Rear of combustion chamber	8.30	12.6	6	0	....	....	....
	12.30	12.6	5.6	0	....	....	....
Test 367:							
Top of fuel bed	7.30	4.4	7.4	9.5	1.2	2.4	.8
	9.30	5.4	0	23.6	7.8	1.2	.2
	11.20	5.2	.2	23.8	5.4	1.8	0
Rear of combustion chamber	7.30	13.3	0	.9	....	....	....
	9.30	15.5	.6	.7	....	....	....
	11.30	14.6	.2	1	....	....	....

It is difficult to say whether the samples collected with the water-jacketed sampler are really representative samples of the furnace gases. Some constituents of the gas may decompose and reunite in different ways when suddenly cooled by the water-cooled surface. Chemical analyses of gas collected at the end of the combustion chamber seldom show much CO or any H_2 and CH_4.

Samples collected at the base of the stack show dilution of 25 to 30 per cent. The following table gives the chemical analyses of some gas samples collected simultaneously at the base of the stack and from the rear of the combustion chamber:

Analyses of samples of gas collected in test 305.

Place.	Time.	CO_2.	O_2.	CO.	CH_4.	Sum.
Rear of chamber	9.00	13.4	4.6	....	....	18
Do	9.30	15.0	3.6	0	0.4	19
Do	10.30	14.4	3.1	0	0	17.5
Do	12.30	15.4	1.8	0	....	17.2
Do	1.30	14.6	3.2	0	....	17.8
Average	....	14.5	3.3	0	....	17.8
Base of stack	9.00	10.0	9.2	0	....	19.2
Do	9.30	11.0	7.8	0	....	18.8
Do	10.30	11.2	7.6	0	....	18.8
Do	12.30	11.0	7.9	0	....	18.9
Do	1.30	10.5	7.9	0	....	18.4
Average	....	10.7	8.1	0	....	18.8

The above analyses give 17.5 and 23.2 pounds of gas, respectively, per pound of carbon.

If the flue-gas analyses determine the control of the fire, it is important that the samples analyzed be collected before the gas is diluted. As it is almost impossible to have a perfectly air-tight boiler setting, it is perhaps best to take the sample from the combustion chamber.

VELOCITY OF COMBUSTION AT VARIOUS POINTS ALONG THE FLAME.

The chemical law of mass action for two reacting substances states that, other things being equal, the number of new molecules of resulting compound (in the present case CO_2) formed per second is proportional to the product of the masses of the reacting substances present per unit of volume (of gases in the present case), these masses being expressed in terms of gram molecules. (The gram molecule of a substance is the weight of the substance, in grams, numerically equal to its molecular weight.) There are two atoms in an ordinary molecule of oxygen gas, each weighing sixteen times as much as an atom of hydrogen. Therefore the molecular weight of gaseous oxygen is 32. The molecular weight of CO is $12+16=28$.

Actual volumetric analyses of the simultaneous compositions of gas samples collected from two points along the gas stream of combustion are given on the following page.

Volumetric analyses of samples of gas collected in test 351.

Place.	CO_2.	O_2.	CO.
Top of fuel bed	12.60	1.70	7.10
Rear of combustion chamber	10.90	8.23	.20

The hydrocarbon and hydrogen values are omitted for this problem, although they sometimes amount to several per cent at the surface of the fire; in this calculation the effect of considering them would simply be to intensify the final conclusion. At the top of the fuel bed there was present by volume 1.70 per cent of oxygen and 7.10 per cent of CO. Multiplying each percentage by its specific gravity (so as to get numbers proportional to the masses present), and dividing in each case by the molecular weights above given, we have:

$$1.70 \times 1.105 \div 32 = 0.0588$$
$$7.10 \times 0.967 \div 28 = .245$$

If we assume that the reaction between CO and O_2 is trimolecular, which is probably the case, because two molecules of CO react with one of O_2, then the rapidity with which CO burns is proportional to $CO \times CO \times O_2$, or $CO^2 \times O_2$, and the rapidity of combustion of CO in the two places is, at the top of the fuel bed, $0.245^2 \times 0.0588 = 0.00353$; at the end of the combustion space, $0.00681^2 \times 0.284 = 0.00001337$. 0.00353 is considerably larger than 0.00001337 and therefore the rapidity of combustion is much greater at the top of the fuel bed than at the end of the combustion space (the difference in temperature being neglected).

The curve of chemical activity would drop off rapidly as the gases proceeded along their path in the combustion chamber, so that if the rates of combustion were plotted as ordinates along a base of travel of gases, the resulting curve would look much like the expansion curve of an engine-indicator diagram.

The practical value of such calculations is that they afford a mathematical verification of a fact frequently observed—that mere length of combustion chamber counts for little compared with some device for thoroughly mixing the gases of the flame stream; one good mixing wall or baffle is probably worth many feet of undisturbed flow.

The possibility that many of the molecules of oxygen gas are dissociated at high temperatures into their component atoms does not affect the above calculation, because there would then be more atoms of oxygen looking for molecules of CO, per volume of gases, in just the proportion that the total volume occupied by a given mass of gases would be increased by the dissociation.

COMBUSTION-CHAMBER BAFFLE WALL.

A baffle wall, constructed of special fire brick, was built in the combustion chamber. The object of this wall was to divert the gases from their straight course in order to mix the free oxygen more thoroughly with the unburnt volatile matter of the coal. It was also intended to act as a heat regenerator, absorbing heat when the temperature of the gases was high, and giving it out when the temperature was low, thus keeping the temperature above the ignition temperature of the distilled gases.

It was learned by experiment that only large blocks made of the best material could stand the high temperature and the slagging action of the gases for any length of time. The baffle wall shown in fig. 34 was built of large fire brick, 18 by 12 by 6 inches, said to be of the best material that could be obtained. The wall was built in three sections. The bottom consisted of seven blocks set on end, forming pillars, on top of which six similar blocks were laid diagonally across. The space between the baffle thus formed and the tile roof was filled with small bricks of good material, so that the spaces between the pillars gave the only passage left for the gases. The object of this construction was to divert the stream of furnace gases, which struck the upper portion of the baffle, and break it into many smaller streams,

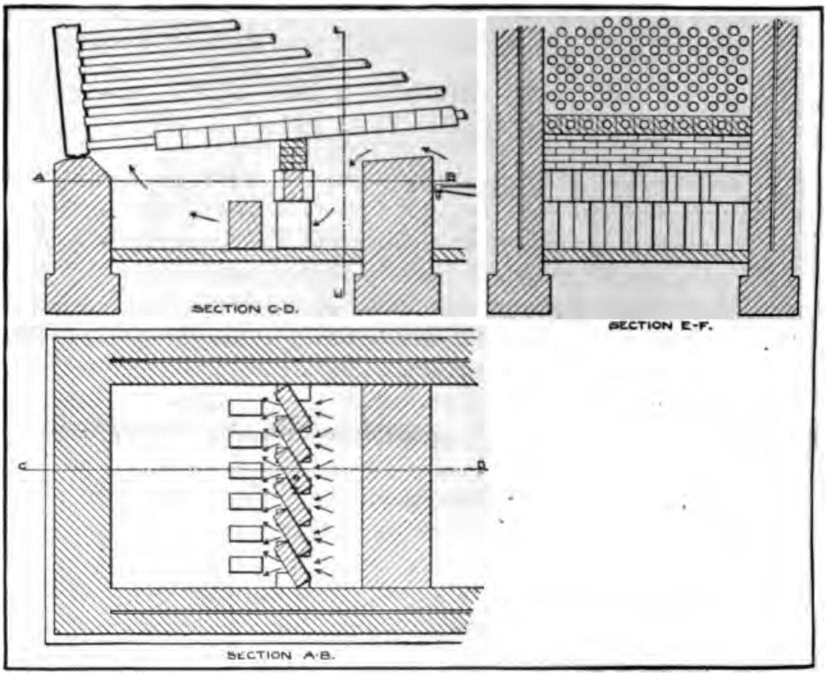


FIG. 34.—Gas-mixing wall built in the Heine safety water-tube boiler.

thus mixing the distilled gases and the free oxygen. It is probable that eddies caused by the obstacles in the path of the gases greatly aided the mixing. The first baffle wall of this construction lasted just six months, but later ones were not so durable, and such walls were finally abandoned, at least temporarily, and replaced by three small piers set on the bridge wall. The first baffles, however, were far more efficient as smoke preventers and heat regenerators, although they absorbed considerably more draft.

COMBUSTION-CHAMBER TEMPERATURE.

Fig. 35 shows the manner in which the "unaccounted-for" and flue losses of about 260 tests vary to some extent inversely. The encircled numbers near the points indicate the number of tests falling within each temperature group. The inverse variation of these curves is a consequence of the facts that the flue-gas analyses, though accurate in themselves, were misleading because of air infiltration, and that the flue temperatures obtained were unreliable because of inherent difficulties; both these causes are discussed in the section devoted to accuracy and reliability of data (pp. 149–151). It is noticeable on this chart that the sum of the flue loss and unaccounted-for loss increases slightly with rise of temperature, notwithstanding the fact that the efficiency of the boiler as a heat absorber increases several per cent with the rise of temperature; thus again the indication is that higher temperatures accompany less complete combustion.

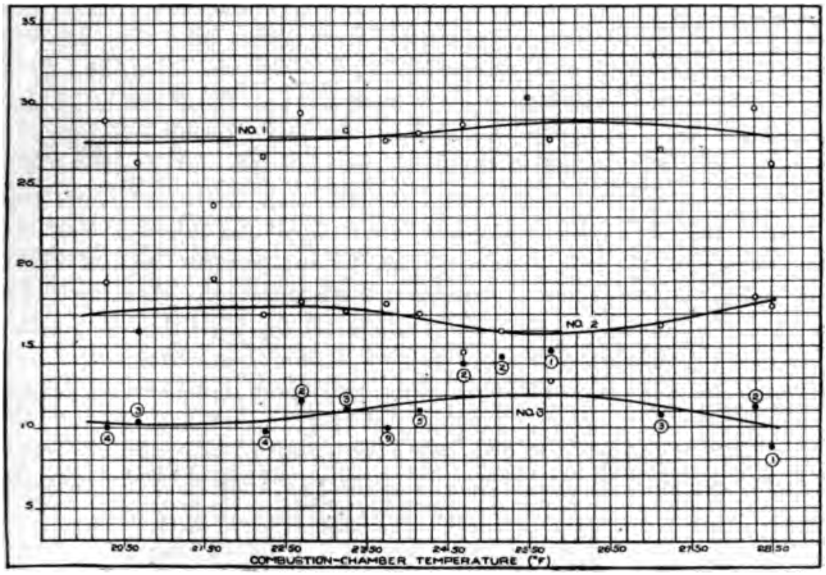


FIG. 35.—Relations of combustion-chamber temperature (°F.) to heat balance (with Illinois and Indiana coals): Curve No. 1, per cent of unaccounted-for loss plus per cent of loss up stack; curve No. 2, per cent of loss up stack; curve No. 3, per cent of unaccounted-for loss.

ATTEMPTS TO EXPLAIN UNACCOUNTED-FOR LOSS IN HEAT BALANCE.

The large percentage of "unaccounted-for" loss appearing in the heat balances of the many tests made by the boiler division has long been a cause of discussion.

The settings of the boilers used for testing the various coals have been, even with the utmost diligence, in a very unsatisfactory condition. There were numerous air leaks, so that the furnace gases were always diluted when they reached the base of the stack. It was thought that this dilution of gases introduced error in the calculation of heat loss up the stack. It also seemed that the radiation loss was larger than it should be.

Recently a new setting has been built and completely inclosed by a sheet-iron casing made with air-tight joints, so that the leakage was reduced to a minimum. The walls of the new setting were built of hollow tiles and this with the addition of a sheet-metal casing should have reduced the radiation loss; at least this loss could not be greater than formerly. Still the unaccounted-for loss continues.

A great many classifications have been made on the data and results obtained from our tests. In all cases a few relations continually appear. The important one in this discussion is that low efficiency is always accompanied by the highest per cent of CO in the flue-gas analysis, and the highest efficiency by the lowest per cent of CO. Moreover, the high CO values always go with the highest combustion-chamber temperatures. It is also found that as the combustion-chamber temperature increases the per cent of black smoke increases.

It is not possible to account for very much of the loss in burning coal by the amount of CO found in the gas analysis. Therefore it seems that this appearance of CO in the gas analysis is indicative of bad conditions, such as an irregular fuel bed or the escape of hydrocarbons unburned.

RELATION OF NITROGEN IN FLUE GASES TO EFFICIENCY 72* AND TO SIZE OF COAL, AND OF PER CENT OF CO TO EFFICIENCY 72*.

The curves of fig. 19 (p. 28), based on tests 89 to 401, inclusive, present a combination of two charts. The upper one classifies the tests on a nitrogen basis. This nitrogen is presumably what is left in the flue gases after subtracting from 100 the sum of the percentages by volume of carbon dioxide, oxygen, and carbon monoxide, neglecting any small traces of hydrocarbons which may have been present and were not determined. Curve No. 1 indicates that the code "boiler efficiency" (72*) increases markedly when the nitrogen content rises from 80 to 81 per cent—that is, when Orsat gas-analysis totals decrease from 20 to 19 per cent. The reader can choose between the many possible conjectures as to the fundamental significance of this curve.

Curve No. 2 indicates that for any size of coal, up to maximum size, two different gas analyses may be obtained. The reader may make whatever conjectures he chooses.

Curve No. 3, in the lower chart, is very significant. It indicates that a volumetric percentage of CO above 0.4 per cent is threatening to efficiency. Inasmuch as these were analyses of flue gases, into which 10 to 50 per cent of air had filtered after the gases of combustion passed through the combustion chamber (p. 64), this CO content represents a much larger value. The significant fact is that an increase of CO content from 0.3 to 1 per cent is of itself sufficient to account for only about one-third of the drop from 65 to 54 per cent in code "boiler efficiency" (72*). Figs. 13 (p. 22) and 14 (p. 23) show that the percentage of CO rises with the temperature of combustion; further, the efficiency of the boiler as a heat absorber increases slightly with a rise of furnace temperature; we therefore reach the inevitable conclusion that at least two-thirds of the large drop in code "boiler efficiency" (72*) with rise of CO is due to incomplete combustion losses not represented by CO, so that high CO is a decided danger signal. Curve No. 1 of fig. 18 (p. 27) shows exactly the same thing, with grouping on a "boiler efficiency" (72*) basis. With CO rising from 0.3 to 0.6 per cent the "efficiency" drops from 60 to 55 per cent. The same range of CO in fig. 19 (p. 28) gives the same amount (65 to 60 per cent) of efficiency drop—though in a different region—which is explained by the fact that in grouping any set of related occurrences in different ways the same tests will not often fall in successive groups. For instance, only part of the tests falling in the middle group in one classification are apt to fall in the middle group in any other classification.

RELATION OF CO_2 IN FLUE GASES TO PER CENT OF COMPLETENESS OF COMBUSTION (E_3).

The curve of fig. 31 (p. 51) was obtained by grouping tests according to volumetric CO_2 content of flue gases and then averaging the per cent of completeness of combustion (E_3) of each group. These values of E_3 were obtained by the mathematical calculation explained on page 139, and although many or all of them may be considerably in error, it is likely that the general shape and the amount of drop of this curve are nearly correct.

The curve shows clearly that as the oxygen is decreased simultaneously with a rise of CO_2 content the completeness of combustion decreases, which is just what we should expect when reducing the proportion of oxygen molecules present, according to the law of mass action discussed on pages 170–172.

Thus even in furnaces as long as those of the boilers used in the work of the boiler division the increasing incompleteness of combustion with rising temperature is practically sufficient to offset an increase of a few per cent in the efficiency of the boiler as a heat absorber after the furnace temperature has reached about 2,400° F.

RELATION OF DIFFERENCES OF DRAFT TO POUNDS OF DRY CHIMNEY GASES PER POUND OF "COMBUSTIBLE."

The curves of fig. 36 were determined by plotting differences between draft in stack and draft over fire with pounds of dry chimney gases per pound of "combustible." Curve No. 1 represents about 200 tests. The values for pounds of dry chimney gases per pound of "combustible" were figured from stack samples. Curve No. 2 is the average of only a few points. The values for pounds of dry

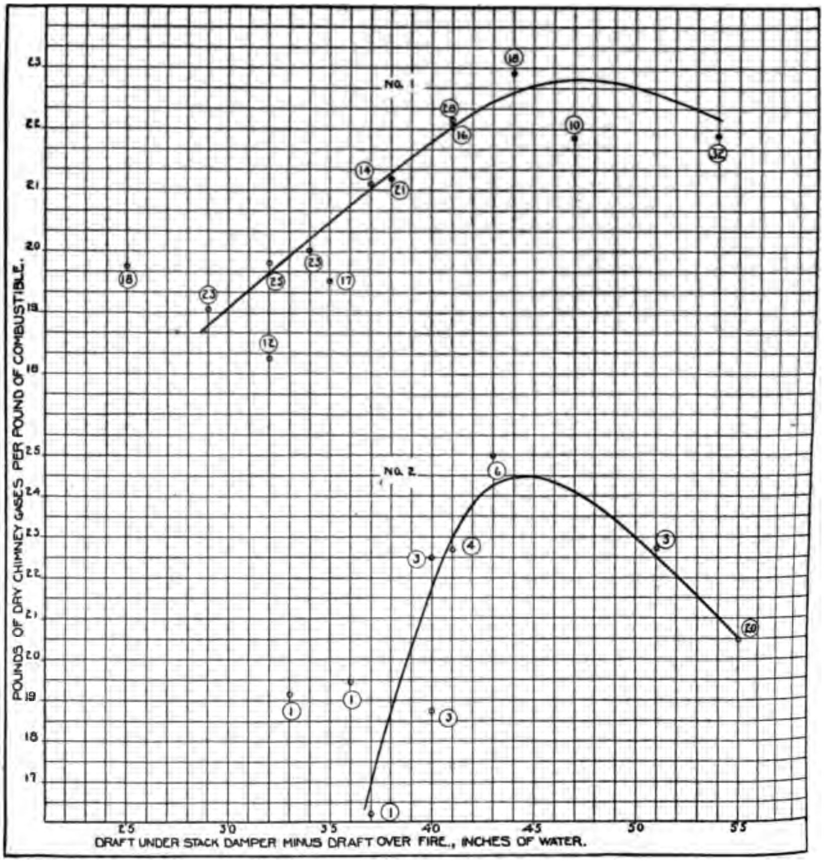


FIG. 36.—Relation of differences between draft in stack and draft over fire to pounds of dry chimney gases per pound of "combustible:" Curve No. 1, figured from analysis of gas in stack, tests 120-400; curve No. 2, figured from analysis of gas in rear of combustion chamber, tests 318-380.

chimney gases per pound of "combustible" were figured from samples taken in the combustion chamber. The general direction of the curve was determined by curve No. 1.

Low difference of draft readings occurs in two ways—by carrying a low-stack draft accompanied by a thin fire or by carrying a high-stack draft and a thick fire. On most of these tests the stack draft is comparatively high as regards the amount of draft obtainable, hence the average points on the low difference of draft may be assumed to result from thick fires.

The use of a thick fire causes resistance to the passage of air through the fuel bed. When high-stack draft is used the difference between the pressure of the gases on the inside of the boiler setting and the atmospheric pressure outside is large, and thereby the absolute amount of leakage of air into the setting is increased. However, since, in general, high-stack draft has been carried, it follows that on the chart the per cent of leakage is a maximum at the points of low-draft differences. That is to say, as the draft difference increases the pounds of dry chimney gases per pound of combustible increase, the per cent of air leakage decreases, and more of the air comes through the fuel bed. This condition holds up to a point where the fire is thin, as indicated by a high-draft difference. The air now enters more freely through the fuel bed, increasing the rate of combustion, thereby decreasing the pounds of dry chimney gases per pound of "combustible." Another cause for the decrease of the pounds of dry chimney gases at the high-draft difference points is the very low per cent of air leakage. Thus it is shown that with two widely varying conditions we may obtain the same weight of dry chimney gases per pound of "combustible."

The curves have no bearing on efficiency. The variation in the slope of curves Nos. 1 and 2 is probably due to air leakage.

The following table gives figures on pounds of dry gases per pound of carbon, calculated from gas analyses taken simultaneously at different parts of the boiler:

Infiltration of air through setting.

Test No.	Pounds of gas per pound of carbon.				Per cent of leakage, combustion chamber to stack.	Test No.	Pounds of gas per pound of carbon.				Per cent of leakage, combustion chamber to stack.
	Over fire.	Combustion chamber.	Front water leg.	Stack.			Over fire.	Combustion chamber.	Front water leg.	Stack.	
318	....	18.38	19.20	23.34	27.0	355	15.29	20.90	25.42	26.78	28.0
319	....	24.02	27.89	32.42	34.9	356	18.22	19.84	22.50	25.28	27.3
320	....	23.76	25.31	28.37	21.5	357	13.65	20.68	18.38	29.12	40.8
321	....	16.85	19.64	23.20	37.7	359	....	21.88	....	26.78	22.4
323	....	16.17	17.88	21.60	33.6	360	....	20.50	....	25.16	22.7
324	....	19.93	23.75	26.51	33.0	361	....	19.04	....	25.49	33.8
325	....	19.44	22.40	27.30	40.4	362	13.27	22.48	19.89	29.70	32.2
326	....	20.38	23.83	31.45	54.3	363	....	21.81	....	27.17	24.4
327	....	23.21	25.50	28.87	24.3	364	12.45	19.15	18.14	25.30	32.1
328	....	17.96	21.00	24.42	35.9	365	....	21.10	....	29.18	38.3
329	....	....	23.38	26.90	....	366	....	22.29	....	26.02	16.8
330	....	....	21.51	25.09	....	367	11.77	18.44	16.85	26.40	43.2
332	....	....	18.62	23.60	....	369	....	21.89	....	27.73	26.7
334	....	....	21.09	24.26	....	370	....	22.22	....	27.78	24.9
344	....	21.70	....	27.85	27.7	371	....	30.90	....	37.05	19.9
347	10.22	19.40	....	26.80	38.1	372	....	19.14	....	24.54	28.2
348	12.12	17.53	....	24.52	39.9	375	....	20.02	....	26.48	32.1
349	7.77	14.76	....	20.86	41.3	376	....	22.48	....	30.05	33.7
349	11.15	15.78	....	....	....	377	....	26.26	....	34.48	31.3
350	10.54	16.31	....	23.41	43.5	378	....	30.48	....	32.05	5.1
351	12.73	22.91	24.25	30.25	32.0	379	....	25.02	....	27.72	10.8
352	....	20.51	26.87	27.21	32.6	380	....	25.80	....	30.70	19.0
353	15.17	22.15	20.61	25.57	15.3	381	....	28.21	....	32.20	14.2
354	....	25.27	27.83	32.00	26.6						

Average per cent increase from surface of fire to combustion chamber, 52.33; from combustion chamber to front leg, 8.43; from front leg to stack, 21.25; from combustion chamber to stack, 28.48.

CLASSIFICATION OF COALS.

CARBON-HYDROGEN RATIO IN AIR-DRIED COAL.

In the belief that coals of approximately the same proportions of constituents, as shown by chemical analysis, should behave more nearly alike when subjected to similar treatment than coals in which the proportions of the constituents vary widely, the following attempts have been made to classify the coals burned by the boiler division, according to their performance under a boiler.

In accordance with the method proposed by Marius R. Campbell,[a] the ratios of carbon to hydrogen in the ultimate analyses of air-dried car samples were computed. One hundred and seventy-four tests on about 75 different coals were employed for this purpose, washed, dried, and briquetted coals being rejected. It was not expected that this classification (fig. 37) would be of as much service as one based on the same ratio of either coal as received or dry coal, since the amount of drying to which a sample is subjected is dependent on the local conditions, which vary from day to day. The statement just made seems to be borne out by the fact that the average points from which the general efficiency curve (No. 1) is derived fall farther from such a curve than is the case with general curves derived from the ratio of carbon to hydrogen, based on either coal as received or dry coal.

---

[a] Prof. Paper U. S. Geol. Survey No. 48, 1906, pp. 156–173.

The ratio of carbon to hydrogen should have been obtained from the ultimate analysis of the boiler-test sample after air drying, but these data were not available. The ratio used is calculated on the air-dried coal of the car sample—a fact which might account for some of the variations of some of the points from the curve.

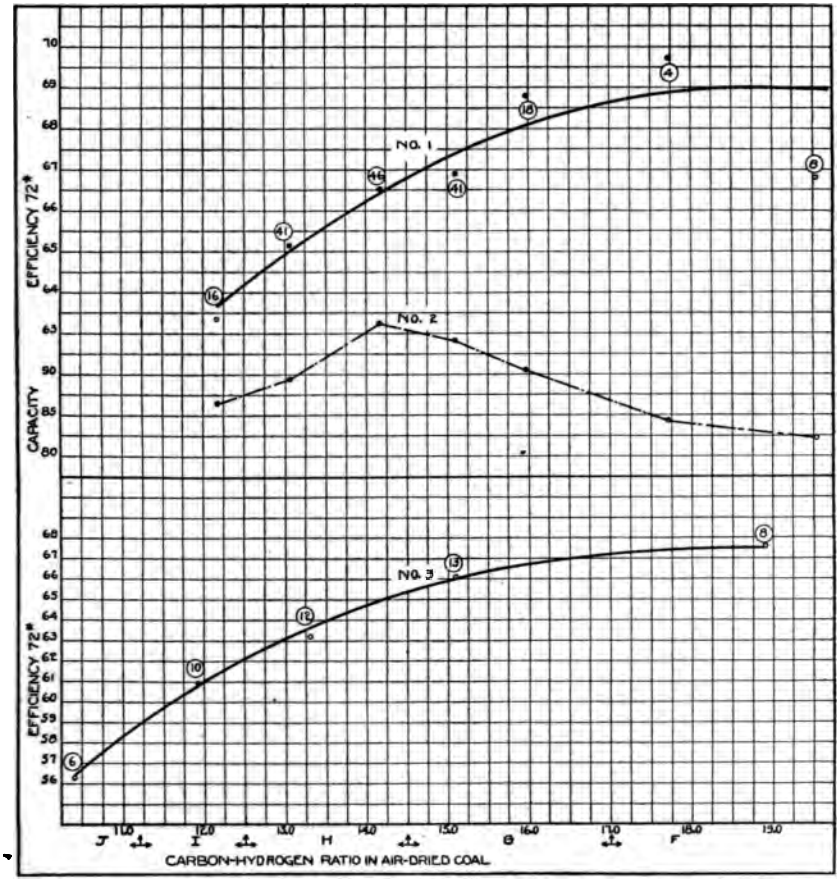


FIG. 37.—Coal classification based on carbon-hydrogen ratio from ultimate analysis of air-dried car samples as related to efficiency 72*, tests 120–401 (curve No. 1); per cent of rated capacity developed (curve No. 2); and efficiency 72* at about rated capacity, tests 1–78 (curve No. 3). General curves, omitting tests of washed, dried, and briquetted coals.

The broken line, curve No. 2, is drawn through the average per cent ratings for all tests coming in each group. The per cent rating attained does not seem to influence the efficiency, as it does in other classifications which follow.

Curve No. 3 shows the relations between carbon-hydrogen ratios on air-dried coal and efficiency from boiler tests conducted during 1904. The tests in which washed and briquetted coals were burned are omitted. It was decided to abandon this classification and to use the ratio of carbon to hydrogen of coal, as received, and of dry coal. The curves and conclusions on classifications based on carbon-hydrogen ratios of coal, as received, and of dry coal, were derived from approximately 250 boiler tests run in one series. The tests included raw, washed, briquetted, and a few mixed coals. The relative values of the classifications were based on the uniformity of the general efficiency curves, efficiency here meaning the efficiency of the boiler on the combustible basis (the combustible consumed, as shown by proximate analysis, less the combustible lost through the grate, as determined by an analysis of the refuse). The item used for the efficiency is 72* of the A. S. M. E. code.

CARBON-HYDROGEN RATIO IN COAL AS RECEIVED.

The carbon-hydrogen ratios of fig. 38 were computed from the ultimate analyses made by the chemical division on boiler-test samples. These ratios were divided into six groups, as follows: Group K, including all values up to 11.2; group L, from 11.2 to 12.5; group M, from 12.5 to 14.5; group N, from 14.5 to 15.5; group O, from 15.5 to 17.0, and group P, all values over 17.0. The several items in each group were then averaged and curves plotted on the basis of (1) efficiency 72*; (2) per cent of CO loss; (3) combustion-chamber temperature (by Wanner optical pyrometer); (4) per cent of rated capacity of boiler; (5) pounds of dry chimney gases per pound of "combustible" (coal free from ash and moisture), and (6) B. t. u. per pound of dry coal.

A comparison of the averages just mentioned shows that no one item was maintained, even approximately, constant, so that whatever conclusions may be drawn therefrom must necessarily be considered anything but absolute. Particular mention should be made of the per cent of rated capacity attained in the trials, which, if maintained constant, might have aided materially in defining more closely the relative causes and effects as indicated by the other items, although it is believed that these items are as much dependent on the kind of coal as on the per cent of rated capacity attained.

The averages of all of the like items of each group are graphically represented on the accompanying charts (figs. 39–45), on which the ratio of carbon to hydrogen appears as an abscissa.

The curves of efficiency 72* in figs. 38 and 39 do not agree; but it is hardly to be expected that items should vary alike when tests are classified on such an illogical basis as the carbon-hydrogen ratio in coal as fired, inasmuch as the hydrogen of the free moisture is also included.

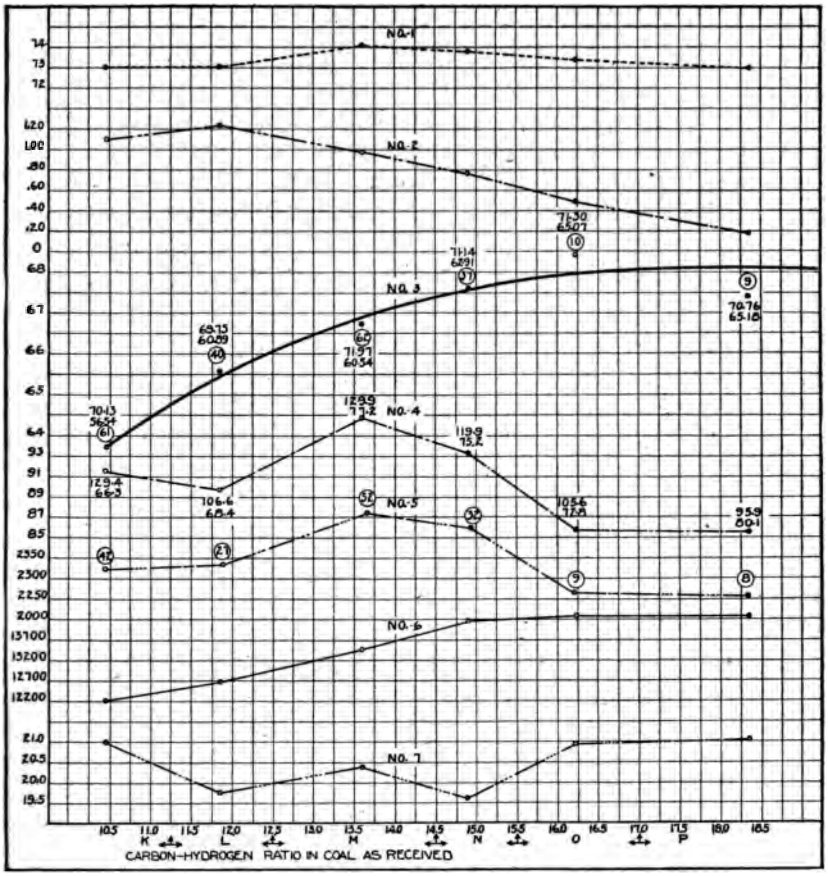


FIG. 38.—Coal classification based on carbon-hydrogen ratio as related to theoretical relative efficiency of boiler as a heat absorber at various temperatures (curve No. 1); per cent of CO loss (curve No. 2); efficiency 72* (curve No. 3); per cent of rated capacity developed (curve No. 4); combustion-chamber temperature (°F.) (curve No. 5); B. t. u. per pound of dry coal (curve No. 6); and pounds of dry chimney gases per pound of "combustible" (curve No. 7). General curves, samples as received, tests 120–380.

The following list gives the coals appearing in each group and their respective carbon-hydrogen ratios:

Average carbon-hydrogen ratios determined from analysis of boiler-test samples of coal as fired, including moisture.

Group P (all values over 17.0):	
Arkansas No. 8	20.32
Maryland No. 1	19.13
Maryland No. 1 (washed)	18.28
Pennsylvania No. 8	18.02
West Virginia No. 19	17.16
Group O (from 15.5 to 17.0):	
West Virginia No. 19	16.93
Arkansas No. 7 A	16.79
West Virginia No. 17	16.27
West Virginia No. 17 (washed)	16.15
Group O (from 15.5 to 17.0)—Continued.	
Virginia No. 3	16.02
Pennsylvania No. 7	15.65
West Virginia No. 18	15.63
Group N (from 14.5 to 15.5):	
Virginia No. 3	15.46
West Virginia No. 14	15.45
Pennsylvania No. 4	15.27
Pennsylvania No. 7 (washed)	15.10
Ohio No. 5	15.15
Pennsylvania No. 6	15.10

Group N (from 14.5 to 15.5)--Continued.

West Virginia No. 13	15.04
West Virginia No. 20	14.97
Virginia No. 4	14.86
West Virginia No. 15	14.84
Virginia No. 2	14.83
Tennessee No. 6	14.78
Kentucky No. 5	14.77
Pennsylvania No. 10	14.74
Pennsylvania No. 7	14.72
West Virginia No. 20 (washed)	14.72
Tennessee No. 9	14.70
Pennsylvania No. 5 (washed)	14.66
West Virginia No. 21	14.57

Group M (from 12.5 to 14.5):

West Virginia No. 21	14.43
Tennessee No. 9	14.40
West Virginia No. 21 (washed)	14.36
Pennsylvania No. 5	14.25
Kentucky No. 1 C	14.17
Kentucky No. 6	14.16
Virginia No. 1 B	14.14
Ohio No. 9 A	14.11
Ohio No. 9 B (washed and dried)	13.98
Ohio No. 5	13.89
Ohio No. 4	13.89
Ohio No. 4 (washed)	13.76
Tennessee No 7 A	13.73
Ohio No. 6 (washed)	13.73
Tennessee No. 2	13.70
Alabama No. 4	13.63
Tennessee No. 1	13.62
Ohio No. 6	13.55
Washington No. 2	13.38
Tennessee No. 5	13.24
Tennessee No. 4	13.04
Tennessee No. 3	13.01
Illinois No. 11 A	12.92
Ohio No. 7	12.76
Illinois No. 16	12.73
Illinois No. 19 B	12.73
Ohio No. 9 B (washed)	12.52

Group L (from 11.2 to 12.5):

Kansas No. 6	12.41
Ohio No. 3 (washed)	12.33
Ohio No. 9 B	12.31
Illinois No. 13 (washed)	12.27
Kentucky No. 7	12.22
Illinois No. 13	12.22
Illinois No. 19 A	12.11
Indiana No. 11	12.00
Illinois No. 12	11.95
Ohio No. 8	11.91

Group L (from 11.2 to 12.5)—Continued.

Illinois No. 12 (washed)	11.85
Ohio No. 2 (washed)	11.77
Indiana No. 7 A	11.71
Ohio No. 2	11.62
Kansas No. 6 (washed)	11.61
Indiana No. 8	11.49
Ohio No. 1	11.47
Indiana No. 7 B	11.43
Indiana No. 7 B (briquetted)	11.38
Ohio No. 1 (washed)	11.38
Illinois No. 22 A	11.35
Indiana No. 5	11.32
Illinois No. 15	11.25
Indiana No. 6	11.21

Group K (all values up to 11.2):

Indiana No. 6 (washed)	11.18
Indiana No. 8 (washed)	11.13
Indiana No. 5	11.12
Illinois No. 15 (washed)	11.07
Illinois No. 22 A	10.98
Illinois No. 9 B	10.95
Illinois No. 24 B	10.92
Illinois No. 7 D	10.91
Indiana No. 12 (washed)	10.87
Indiana No. 10 (washed)	10.86
Indiana No. 9 A	10.84
Illinois No. 14	10.83
Indiana No. 9 B	10.80
Indiana No. 10	10.79
Wyoming No. 2 B	10.79
Indiana No. 4 (washed)	10.75
Illinois No. 18	10.70
Indiana No. 12	10.68
Missouri No. 6	10.67
Illinois No. 22 A (washed)	10.65
Indiana No. 4	10.52
Illinois No. 25	10.51
Missouri No. 5	10.47
Illinois No. 21	10.46
Illinois No. 26	10.43
Indiana No. 3	10.38
Illinois No. 20	10.15
Illinois No. 23 A (washed)	10.10
Illinois No. 14 (washed)	10.09
Illinois No. 18 (washed)	10.03
Illinois No. 20 (washed)	9.96
Mixed coal	9.95
Illinois No. 23 A	9.90
Illinois No. 7 C (washed)	9.82
Illinois No. 27	9.71
Missouri No. 7 (washed)	9.67
Washington No. 1 B	9.61
Wyoming No. 3	9.44
Wyoming No. 3 (washed)	8.94

The curve drawn along the average-efficiency points on the chart is so uniform that the conclusion might easily be reached that a classification such as the ratio of carbon to hydrogen is of great value. If an individual group is selected there is no such close agreement, as is shown by the range of efficiencies noted at each point of the general-efficiency curve. The curve shows a gradual increase of efficiency as the ratio of carbon to hydrogen increases, becoming horizontal for the high ratios.

A comparison of the highest efficiencies of the groups shows a marked uniformity. The range of efficiencies in each group (not shown on the chart) decreases as the ratio of carbon to hydrogen increases, seeming to indicate that efficient burning of coals of a lower carbon-hydrogen ratio is a matter of much greater uncertainty than when the ratio is high.

The curve of per cent of CO loss indicates maximum incomplete combustion in the low-ratio groups, decreasing to nearly zero in the high-ratio groups. This is in accord with the statement made regarding the uncertainty of burning coals of a low carbon-hydrogen ratio.

The B. t. u. curve, No. 6, rises as the carbon-hydrogen ratio increases.

A broken line connecting the averages of the per cent of rated capacity of each group is shown, curve No. 4. This line points out a wide variation in capacity attained. The figures given with each point on the general curve show a much wider range of the same item as between the different trials of each group than between groups. The variation of per cent of rating tended to remove the average efficiency from a uniform efficiency curve; the average efficiency increased, in general, as the average per cent of rating decreased.

From the points showing combustion-chamber temperature we obtain a broken line which is very nearly parallel to the line of per cent of rated capacity, as on many other charts. The highest temperatures were obtained in the middle groups, the lowest temperatures in the highest groups.

The line representing the number of pounds of dry chimney gases per pound of combustible (curve No. 7) can best be studied on the charts of the separate groups; on the general chart it is difficult to arrive at conclusions so far as this one item is concerned.

Curve No. 1 in the chart is merely tentative and is put on to show relatively the theoretical efficiency of the boiler as an absorber of heat generated, the calculation being based on the theory, developed on pages 107–108, that the heat absorption is a function varying slightly with combustion-chamber temperature; for this purpose the temperatures used are those on the line of combustion-chamber temperatures. It will be noticed that the line of theoretical boiler efficiencies varies less than 2 per cent; it may be too high or too low at every point by 2 per cent, but it does *show that* in the lower groups the distance is greater between this line and that of efficiency 72*. This fact seems to indicate that in the lower groups there was more incomplete combustion—an indication which is verified by curve No. 2, giving per cent of CO loss. It is noteworthy that the best actual efficiencies 72* in all groups were about the same (a fact which is not shown on the chart), indicating that when enough is known about combustion and when special grates, stokers, furnaces, etc., are applied, it will be possible to burn very poor coals with nearly the same efficiencies as good ones.

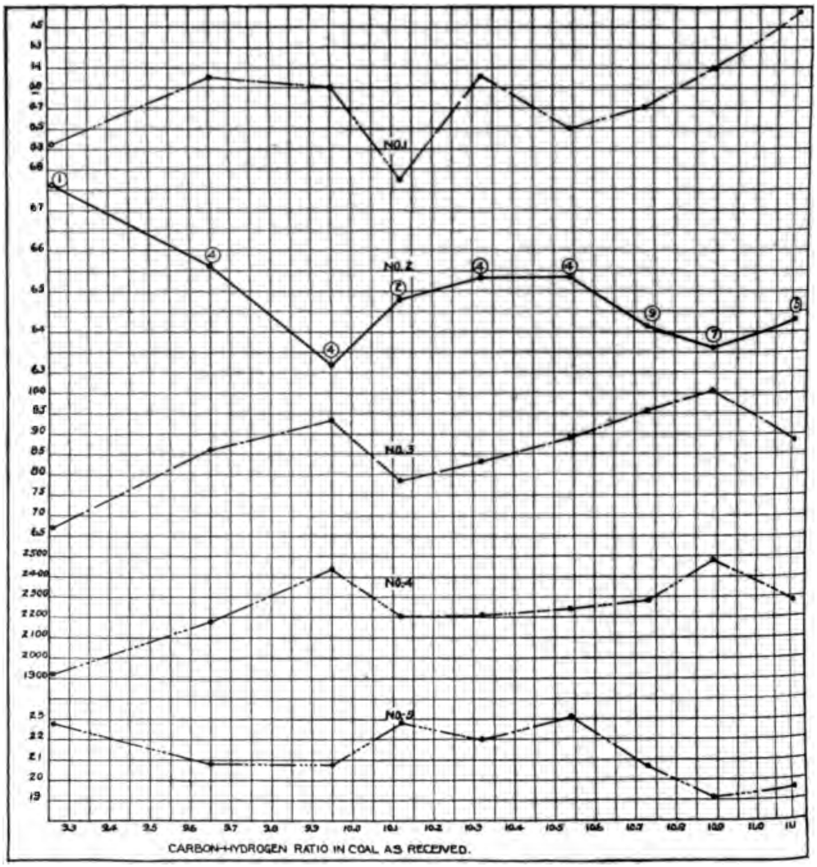


FIG. 39.—Coal classification based on carbon-hydrogen ratio as related to per cent of CO loss (curve No. 1); efficiency 72* (curve No. 2); per cent of rated capacity developed (curve No. 3); combustion-chamber temperature (°F) (curve No. 4); and pounds of dry chimney gases per pound of "combustible" (curve No. 5). Group K, all values up to 11.2, samples as fired.

In order to discover the variations within the individual groups three charts have been plotted involving the same items as shown on the general chart.

Since the general curve shows a gradual increase in efficiency with an increase of the ratio of carbon to hydrogen, one would naturally look for a similar increase in efficiency within individual groups. This is not true, however, because of wide variations in the other items within each group.

The efficiency line (fig. 39) in group K varies inversely with the per cent of rating and to a much more marked degree than in the general chart. Also the efficiency falls as the combustion-chamber temperature rises, and vice versa. The line for combustion-chamber temperature is parallel to the line for per cent of rating, as in many other places.

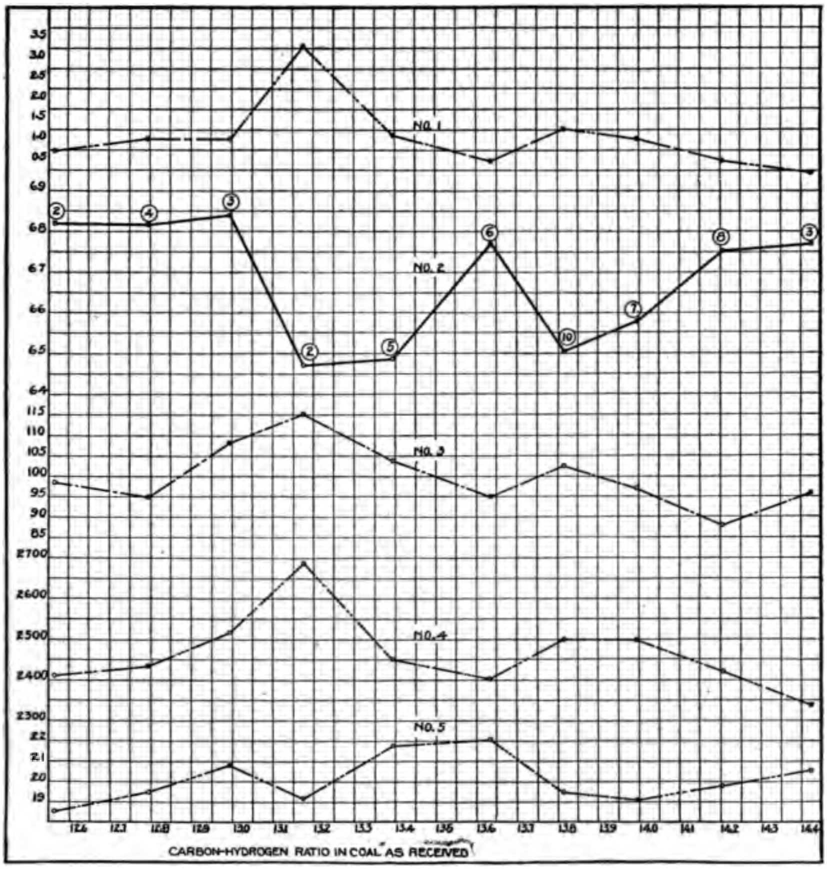


FIG. 40.—Coal classification based on carbon-hydrogen ratio as related to per cent of CO loss (curve No. 1); efficiency 72* (curve No. 2); per cent of rated capacity developed (curve No. 3); combustion-chamber temperature (°F) (curve No. 4); and pounds of dry chimney gases per pound of "combustible" (curve No. 5). Group M, values from 12.5 to 14.5, samples as fired.

The line for per cent of CO loss varies inversely with the line for pounds of dry chimney gases per pound of "combustible," as would be expected from the chemical law of mass action; and in turn the line denoting pounds of air per pound of "combustible" runs parallel in most places with the efficiency line.

Fig. 40 shows that for group M the lines representing the per cent of rating, combustion-chamber temperature, and per cent of CO loss run parallel to one another and vary inversely with the line giving pounds of dry chimney gases per pound of combustible and also in a general way, inversely with the efficiency line; all of which interrelations are much the same as in group K (fig. 39). Relations between variables are brought out very clearly in fig. 40. The general chart shows that group M was the one in which the highest combustion-chamber temperatures and the highest per cent of rating were obtained.

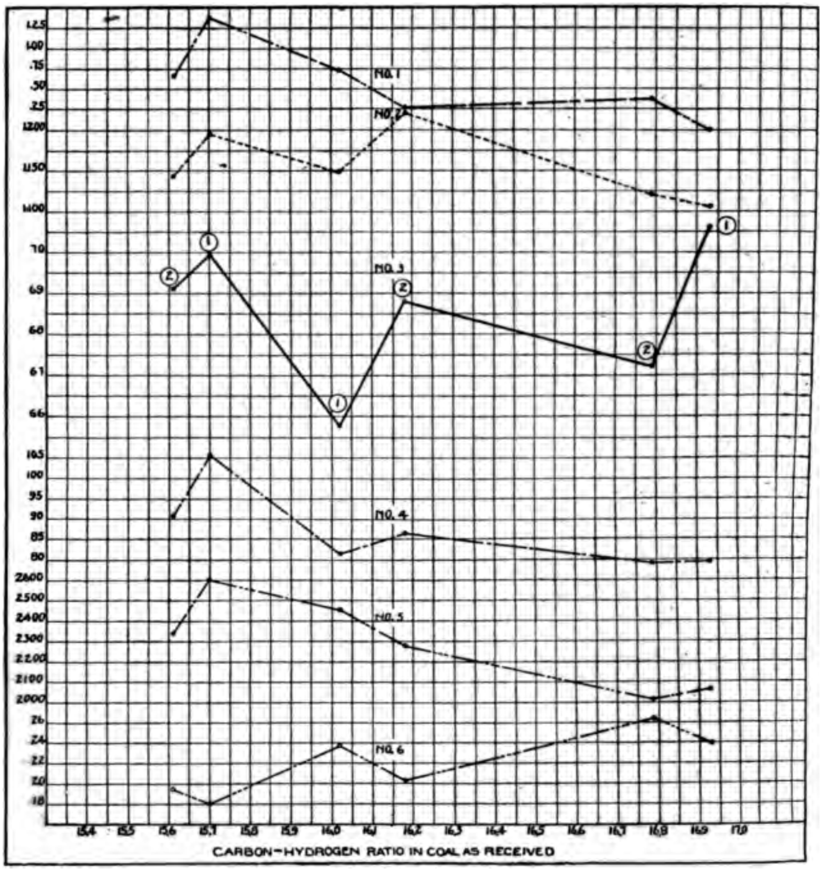


FIG. 41.—Coal classification based on carbon-hydrogen ratio as related to per cent of CO loss (curve No. 1); ratio of hydrogen to available hydrogen (curve No. 2); efficiency 72* (curve No. 3); per cent of rated capacity developed (curve No. 4); combustion-chamber temperature (°F) (curve No. 5); and pounds of dry chimney gases per pound of "combustible" (curve·No. 6). Group O, values from 15.5 to 17.0, samples as fired.

In group O (fig. 41) the lines of combustion-chamber temperature and per cent of rating are shown parallel with the efficiency line. The per cent of CO loss is small at all times in this group, so little effect could be expected from this cause. The additional curve showing the ratio of hydrogen to available hydrogen is parallel to the efficiency line. The line for pounds of dry chimney gases, instead of being parallel with the efficiency line, as in other groups, varies inversely with that line, a variation that is concordant with the fact that the small CO loss indicates very little incomplete combustion.

CARBON-HYDROGEN RATIO IN DRY COAL.

Another classification has been made (fig. 25, p. 37) by using the ratio of carbon to total hydrogen, as determined by the ultimate analysis of dry coal. By this method that portion of the hydrogen which appears in the moisture determined by the proximate analyses is eliminated, and consequently there should result a more nearly constant carbon-hydrogen ratio for any given coal. The ratios were divided into seven groups, as follows: Group A, including all values up to 14.5; group B, from 14.5 to 15.0; group C, from 15.0 to 15.5; group D, from 15.5 to 16.0; group E, from 16.0 to 16.5; group X, from 16.5 to 17.5; group Y, all values of 17.5 and over.

As in the previous classification (p. 70) all the values in each group were averaged and each average was plotted with its corresponding average of carbon-hydrogen ratio. The following list shows the coals in each group and their corresponding carbon-hydrogen ratios:

Average carbon-hydrogen ratios determined from ultimate analysis of dry coal.

Group Y (all values of 17.5 and over):	
Arkansas No. 8	22.60
Maryland No. 1	20.16
Maryland No. 1 (washed)	20.14
Arkansas No. 7 A	19.50
Pennsylvania No. 8	19.37
West Virginia No. 19	18.23
West Virginia No. 17	17.92
West Virginia No. 17 (washed)	17.91
Group X (from 16.5 to 17.5):	
Pennsylvania No. 7	17.04
Pennsylvania No. 7 (washed)	17.03
West Virginia No. 18	16.71
Illinois No. 19 A	16.67
Virginia No. 3	16.64
Kentucky No. 5	16.56
Group E (from 16 to 16.5):	
West Virginia No. 14	16.45
West Virginia No. 13	16.44
Ohio No. 9 A	16.38
Illinois No. 19 B	16.21
Virginia No. 4	16.13
Pennsylvania No. 4	16.11
Pennsylvania No. 6	16.07
Tennessee No. 9	16.01
Group D (from 15.5 to 16.0):	
Virginia No. 2	15.96
Tennessee No. 6	15.90
Group D (from 15.5 to 16.0)—Continued.	
Illinois No. 16	15.85
West Virginia No. 20	15.85
West Virginia No. 20 (washed)	15.81
Indiana No. 11	15.78
Virginia No. 1 B	15.73
Kentucky No. 6	15.72
West Virginia No. 21	15.71
West Virginia No. 21 (washed)	15.71
Pennsylvania No. 10	15.65
Pennsylvania No. 5	15.64
Pennsylvania No. 5 (washed)	15.63
West Virginia No. 15	15.58
Illinois No. 11 A	15.57
Kentucky No. 1 C	15.54
Group C (from 15 to 15.5):	
Illinois No. 13	15.46
Illinois No. 13 (washed)	15.43
Ohio No. 5	15.37
Alabama No. 4	15.29
Kentucky No. 7	15.29
Tennessee No. 2	15.26
Kansas No. 6	15.21
Kansas No. 6 (washed)	15.20
Tennessee No. 5	15.17
Ohio No. 3 (washed)	15.09
Ohio No. 4	15.08
Ohio No. 4 (washed)	15.07

Group C (from 15 to 15.5)—Continued.

Tennessee No. 1	15.04
Illinois No. 21	15.03
Indiana No. 4	15.01
Indiana No. 4 (washed)	15.01
Illinois No. 12	15.00

Group B (from 14.5 to 15.0):

Indiana No. 4	14.99
Illinois No. 12	14.97
Illinois No. 12 (washed)	14.94
Tennessee No. 4	14.94
Ohio No. 9 B (washed)	14.94
Ohio No. 9 B	14.93
Mixed coal	14.92
Illinois No. 26	14.86
Illinois No. 22 A	14.77
Tennessee No. 3	14.77
Tennessee No. 7 A	14.77
Illinois No. 22 A (washed)	14.76
Ohio No. 7	14.76
Ohio No. 6	14.74
Ohio No. 6 (washed)	14.71
Missouri No. 6	14.70
Illinois No. 20	14.63
Illinois No. 20 (washed)	14.61
Indiana No. 5	14.59
Illinois No. 24 B	14.56
Missouri No. 7 (washed)	14.51

Group A (all values up to 14.5):

Ohio No. 9 B (washed and dried)	14.48
Indiana No. 8 (washed)	14.48
Indiana No. 8	14.46
Indiana No. 12	14.46
Indiana No. 12 (washed)	14.45

Group A (all values up to 14.5)—Cont'd.

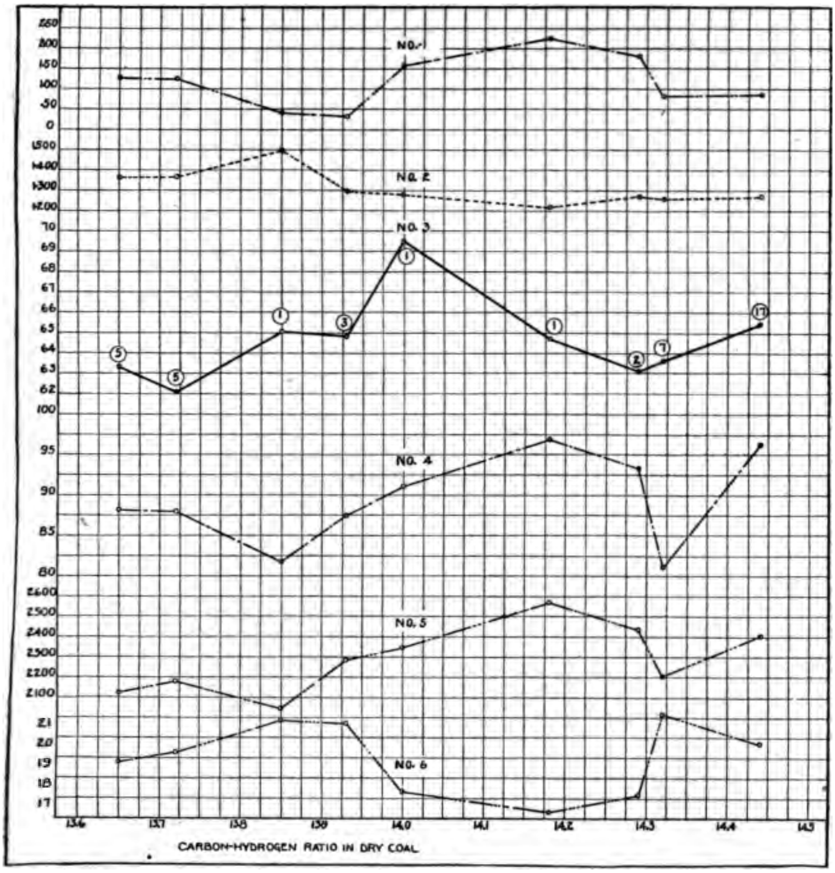
Illinois No. 14	14.45
Washington No. 2	14.45
Mixed coal	14.43
Indiana No. 9 A	14.42
Ohio No. 8	14.42
Illinois No. 14 (washed)	14.42
Illinois No. 15 (washed)	14.40
Indiana No. 7 B (briq.)	14.40
Illinois No. 15	14.39
Indiana No. 7 B	14.36
Missouri No. 5	14.34
Ohio No. 2	14.32
Ohio No. 2 (washed)	14.30
Illinois No. 27	14.30
Indiana No. 6	14.30
Indiana No. 6 (washed)	14.29
Indiana No. 7 A	14.18
Illinois No. 7 C (washed)	14.14
Illinois No. 7 D	14.11
Indiana No. 3	14.01
Illinois No. 9 B	13.96
Indiana No. 9 B	13.95
Illinois No. 23 A (washed)	13.93
Illinois No. 23 A	13.92
Washington No. 1 B	13.85
Illinois No. 25	13.81
Ohio No. 1 (washed)	13.75
Ohio No. 1	13.73
Illinois No. 18 (washed)	13.71
Wyoming No. 2 B	13.71
Wyoming No. 3	13.69
Wyoming No. 3 (washed)	13.68
Illinois No. 18	13.67
Indiana No. 10 (washed)	13.6[illegible]
Indiana No. 10	13.5[illegible]

There is no particular difference in the general curves as derived from the two classifications based on dry coal and coal as received. To the general chart (p. 37) two more curves have been added—one for average diameter of coal (No. 7), and one for per cent of clinker in refuse (No. 8). The curve of average diameter of coal as fired shows that as the ratios of carbon to hydrogen increase there is a gradual reduction in average diameter. Nearly all the coals used in the tests passed through the same crusher. It is not to be assumed that the ratio of carbon to hydrogen influences the ease with which the coal breaks, for this can be accounted for in other ways. The coals of low carbon-hydrogen ratio give the highest per cent of clinker in refuse.

Curve No. 1, theoretical efficiency of boiler as a heat absorber at temperature below, is relative only; it is probably as a whole either o high or too low, and the various points of it may be high or low relative to one another, but it serves its general purpose—to show less complete combustion of the coals low in carbon-hydrogen ratio. The distance between this curve and the efficiency 72* curve is greater the lower the carbon-hydrogen ratio.

Four charts were made detailing groups A, B, D, and Y.

In group A the lines (fig. 42) representing per cent of rating, per cent of CO loss, and combustion-chamber temperature are parallel o one another, and their slope is inverse, in a general way, to that of the lines representing hydrogen over available hydrogen and pounds of dry chimney gases per pound of "combustible." This group contains tests varying 13 per cent in efficiency, indicating the uncertainty of attaining the higher efficiency with coals of low carbon-hydrogen ratio. No other relations occur in this group such as occur in the higher groups.



IG. 42.—Coal classification based on carbon-hydrogen ratio as related to per cent of CO loss (curve No. 1); ratio of hydrogen to available hydrogen (curve No. 2); efficiency 72* (curve No. 3); per cent of rated capacity developed (curve No. 4); combustion-chamber temperature (° F.) (curve No. 5); and pounds of dry chimney gases per pound of "combustible" (curve No. 6). Group A, all values up to 14.5, dry coal.

Group B gives very marked relations. The lines (fig. 43) representing the per cent of rating, combustion-chamber temperature, per cent of CO loss, efficiency 72*, and per cent of clinker in refuse run in the same general direction and the values vary inversely with the pounds of dry chimney gases per pound of "combustible" and hydrogen over available hydrogen. Why the line for efficiency 72* should parallel the line of CO loss is not clear, especially as the latter is high and the combustion-chamber temperature varies but little; however, not many tests are considered.

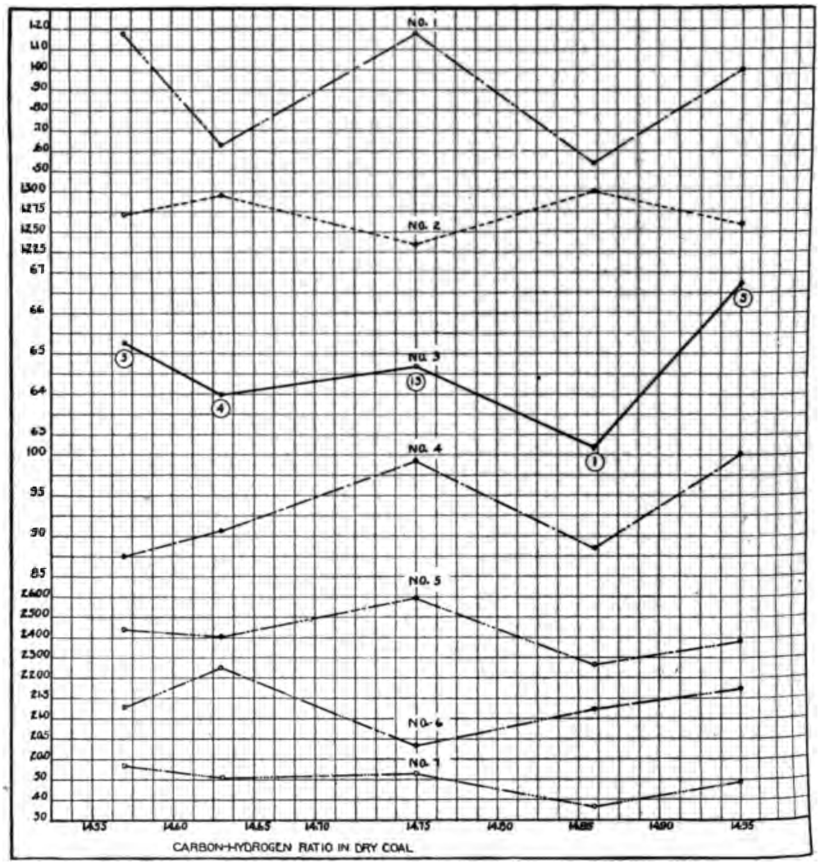


FIG. 43.—Coal classification based on carbon-hydrogen ratio as related to per cent of CO loss (curve No. 1); ratio of hydrogen to available hydrogen (curve No. 2); efficiency 72* (curve No. 3); per cent of rated capacity developed (curve No. 4); combustion-chamber temperature (° F.) (curve No. 5); pounds of dry chimney gases per pound of "combustible" (curve No. 6); and per cent of clinker in refuse (curve No. 7). Group B, values from 14.5 to 15.0, dry coal.

In group D (fig. 44) the lines representing the per cent of rating, combustion-chamber temperature, per cent of CO loss, and per cent of clinker in refuse are parallel to one another, and for the most part that of hydrogen over available hydrogen follows the three in direction. The curves for efficiency and pounds of dry chimney gases per pound of "combustible" are parallel to each other and run inversely with all the rest.

The same characteristics appear in group Y (fig. 45) as in group D (fig. 44).

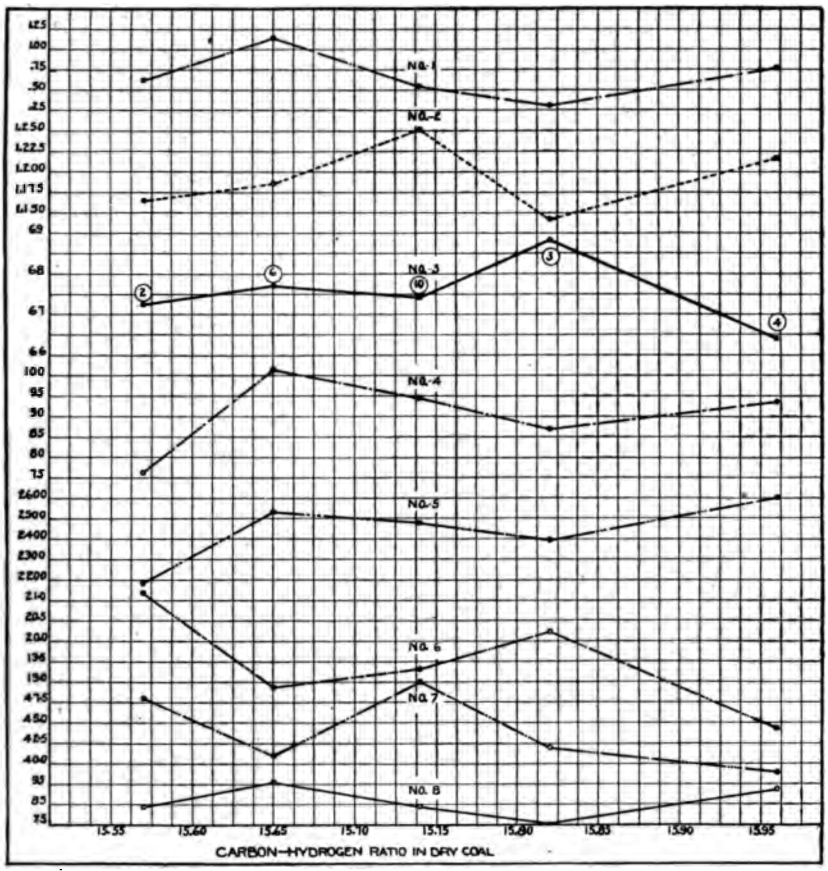


FIG. 44.—Coal classification based on carbon-hydrogen ratio as related to per cent of CO loss (curve No. 1); ratio of hydrogen to available hydrogen (curve No. 2); efficiency 72* (curve No. 3); per cent of rated capacity developed (curve No. 4); combustion-chamber temperature (° F.) (curve No. 5); pounds of dry chimney gases per pound of "combustible" (curve No. 6); per cent of clinker in refuse (curve No. 7); and average diameter of coal (curve No. 8). Group D, values from 15.5 to 16.0, dry coal.

Attempts were also made to classify coals according to the available hydrogen figured from the "combustible" in the coal; according to the ratio of carbon to available hydrogen, and according to the moisture over the per cent of air-drying loss. None of these were of much value.

CARBON-HYDROGEN RATIO IN COAL AS FIRED AS AFFECTING EFFICIENCY 72*.

Fig. 46 shows the effect of the carbon-hydrogen ratio of coal as received (fired) on efficiency 72* for each of three capacity groups. The curves determined by plotting efficiency 72* with carbon-hydrogen ratio for a nearly constant per cent of rating are very uniform.

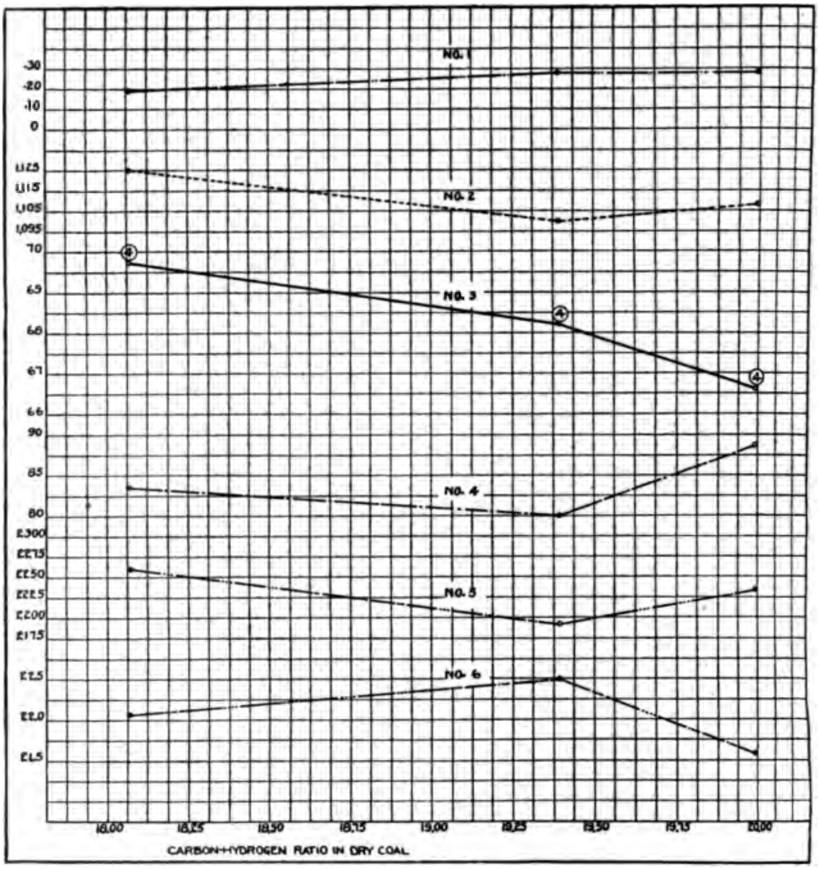


FIG. 45.—Coal classification based on carbon-hydrogen ratio as related to per cent of CO loss (curve No. 1); ratio of hydrogen to available hydrogen (curve No. 2); efficiency 72* (curve No. 3); per cent of rated capacity developed (curve No. 4); combustion-chamber temperature (° F.) (curve No. 5); and pounds of dry chimney gases per pound of "combustible" (curve No. 6). Group Y, values of 17.5 and over, dry coal.

Three curves were plotted, Nos. 1, 2, and 3, at capacities of 95 to 105, 85 to 95, and 75 to 85, respectively. The efficiency 72* range on any one curve decreases as the per cent of rated capacity decreases. A probable explanation of this chart is that, with the low carbon-hydrogen ratios, the efficient burning of coal is rather uncertain. As the capacity is increased the combustion-chamber temperature is raised; therefore the high-rating curves are the high-temperature curves. This relation probably has considerable to do with the efficiency ranges on the three curves. It is also evident from this chart that the high capacities were obtained with the coals of low and medium carbon-hydrogen ratios.

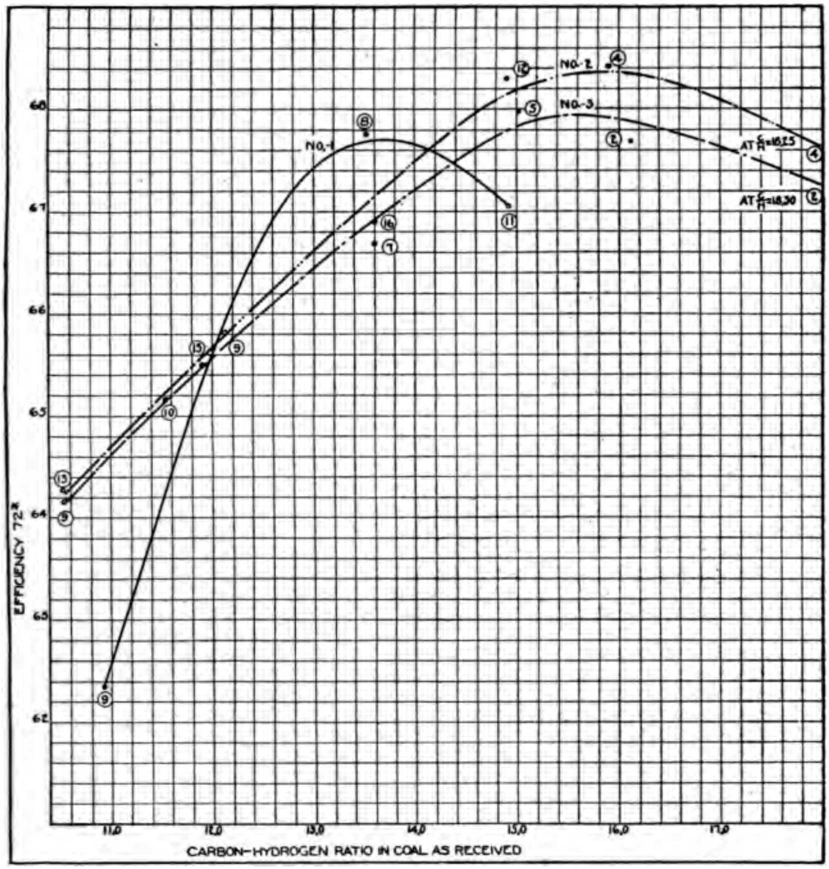


Fig. 46.—Coal classification based on per cent of rating. Efficiency curves: No. 1, from 95 to 105 per cent; No. 2, from 85 to 95 per cent; No. 3, from 75 to 85 per cent.

RELATION OF RATIO OF CARBON TO AVAILABLE HYDROGEN AND OF PER CENT OF AVAILABLE HYDROGEN TO EFFICIENCY 72*.

Fig. 47 is a graphic representation of efficiency 72* on the basis of ratio of carbon to available hydrogen. As this ratio increases there is a considerable increase in efficiency 72*, but the curve is very irregular. Curves Nos. 1 and 2 are similar, but are from two different series of tests. Curve No. 3 is a representation of efficiency 72* on an available hydrogen basis. The efficiency varies but little over the entire range of available hydrogen ratio.

The subjoined table shows two classifications based on the ratio of per cent of "volatile carbon"[a] to per cent of total carbon. The first (column 1) gives average efficiency 72* for average ratio of volatile carbon to total carbon values, showing that for the low ratio values we have the high efficiency 72* values and vice versa. There is, however, as the chart (fig. 48) shows, no uniformity of drop in efficiency as the value of the ratio increases. The second classification (columns 2–7) gives the values of average efficiency 72*

---

[a] For definition of "volatile carbon" see glossary (p. 183). For information on the "volatile carbon" of coals see Parr, S. W., Bull. Illinois Geol. Survey No. 3, Urbana, Ill.

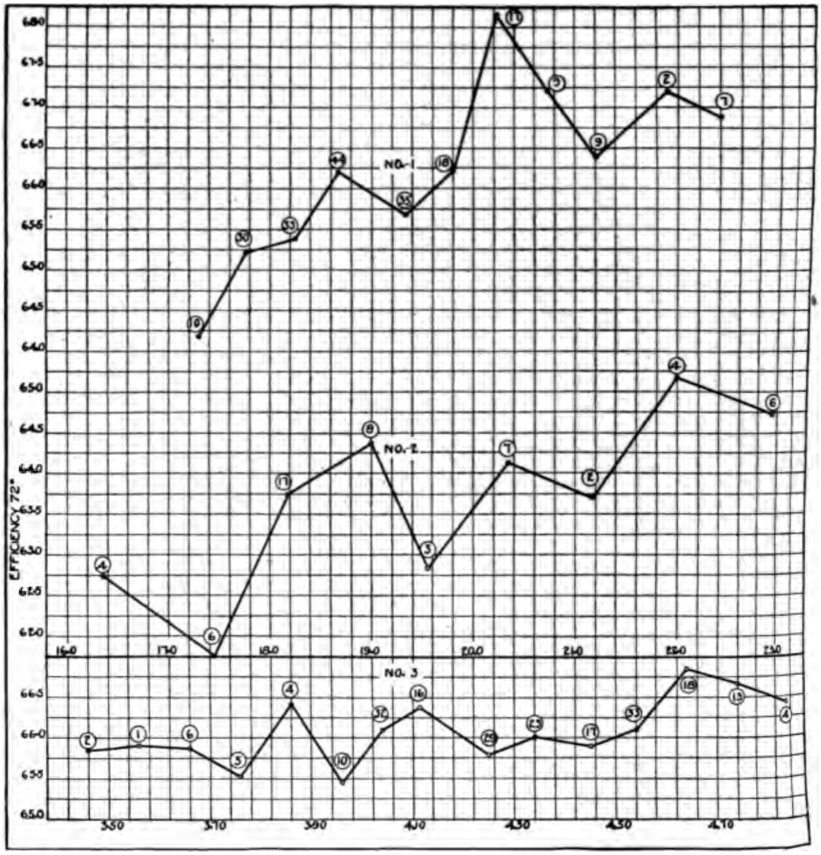


FIG. 47.—General curves showing classification of tests: No. 1 (tests 120–380) and No. 2 (tests 1-78), based on ratio of carbon to available hydrogen; No. 3 (tests 120–380), based on available hydrogen.

for the average values of the volatile carbon to total carbon, grouping them according to the number of B. t. u. supposedly evolve per square foot of grate surface per hour, and shows the same ge eral relations as the preceding classification. The explanation m be that coals high in the ratio of volatile carbon to total carbon a harder to burn than those in which that ratio is low.

Classifications of efficiency 72 on basis of average ratio of volatile carbon to total carbon.*

Range of average ratio.	First classification—not grouped.	Second classification—grouped according to 10,000's of B. t. u. supposedly evolved per square foot of grate surface per hour.					
		Under 22.	22 to 24.	24 to 26.	26 to 28.	28 to 30.	30 and over.
	1.	2.	3.	4.	5.	6.	7.
Under 15:							
Number of tests	16	6	6	1	2	1	
Average ratio × 100	7.25	8.06	8.87	8.97	6.41	2.56	
Average efficiency 72*	67.35	68.20	67.34	65.18	68.10	62.92	
From 15 to 17:							
Number of tests	3	1	1				1
Average ratio × 100	15.94	16.14	16.65				15.04
Average efficiency 72*	65.63	68.51	67.24				61.13
From 17 to 19:							
Number of tests	1					1	
Average ratio × 100	18.75					18.75	
Average efficiency 72*	63.63					63.63	
From 19 to 21:							
Number of tests	5	1	1	2	1		
Average ratio × 100	20.16	20.09	20.52	19.95	20.30		
Average efficiency 72*	65.59	68.21	63.40	65.27	65.78		
From 21 to 23:							
Number of tests	18	1	5	5	1		
Average ratio × 100	22.18	21.97	22.24	21.85	22.10		
Average efficiency 72*	64.97	67.08	67.27	68.06	65.06		
From 23 to 25:							
Number of tests	28		5	9	4		
Average ratio × 100	24.08		23.65	24.56	24.15		
Average efficiency 72*	67.22		68.83	67.19	69.32		
From 25 to 27:							
Number of tests	52	6	10	10	4	11	3
Average ratio × 100	26.10	26.27	26.28	26.16	26.05	26.01	26.50
Average efficiency 72*	66.42	67.58	67.09	68.96	65.84	64.70	66.51
From 27 to 29:							
Number of tests	63	7	5	14	7	7	6
Average ratio × 100	27.91	28.05	27.76	27.84	27.91	27.47	27.90
Average efficiency 72*	65.64	66.98	66.33	66.08	65.49	65.43	63.76
From 29 to 31:							
Number of tests	33	4	4	3	8	1	4
Average ratio × 100	29.94	29.54	30.25	29.86	29.82	30.03	30.28
Average efficiency 72*	63.87	66.48	66.55	63.86	64.12	61.70	61.17
From 31 to 33:							
Number of tests	37	6	11	13	2	4	
Average ratio × 100	31.86	31.69	31.94	31.86	31.46	31.81	
Average efficiency 72*	64.70	66.05	64.67	64.64	61.71	65.16	
From 33 to 35:							
Number of tests	10	1	2	4		2	1
Average ratio × 100	33.82	34.32	33.89	33.89		33.78	33.03
Average efficiency 72*	62.96	62.18	59.55	64.71		63.83	61.88
Over 35:							
Number of tests	9		1	1	2		5
Average ratio × 100	36.81		35.15	38.38	35.17		37.23
Average efficiency 72*	58.14		60.25	61.37	61.70		55.95

RATIO OF HYDROGEN TO AVAILABLE HYDROGEN.

The ratio of hydrogen to available hydrogen was computed on about 200 ultimate analyses of dry coals using boiler-test samples (see fig. 49). This ratio and also the ratio of carbon to available hydrogen were suggested by Fred M. Stanton, of the chemical laboratory of this plant. These ratios were grouped according to values, as follows: Group R, all values up to 11.0; group S, from 11.0 to 12.0; group T, from 12.0 to 13.0; group U, from 13.0 to 14.0; and group V, 14.0 and over.

Curves showing the relations between the ratio of hydrogen to available hydrogen and efficiency 72*, per cent of rated capacity, per cent of CO loss, and combustion-chamber temperature were obtained by averaging the total number of values for each of these ratio groups and plotting this average against the average of the ratios for the corresponding groups. The resulting efficiency line shows a gradual fall with an increase of the ratio of hydrogen to available hydrogen. The per cent of CO loss shows a gradual increase in value. The lines for per cent of rated capacity and combustion-chamber temperature are parallel and have maximum points where the ratio of hydrogen to available hydrogen has a value of about 1.25, this being the middle of the values for ratio of hydrogen to available hydrogen. The efficiency seems to be independent of both per cent of rating attained and combustion-chamber temperature. The range of efficiency for each group is shown by the figures near each point of the efficiency line. The range decreases, as in the other classifications, as the region of better coals is approached; likewise the best tests of all groups are about equally good.

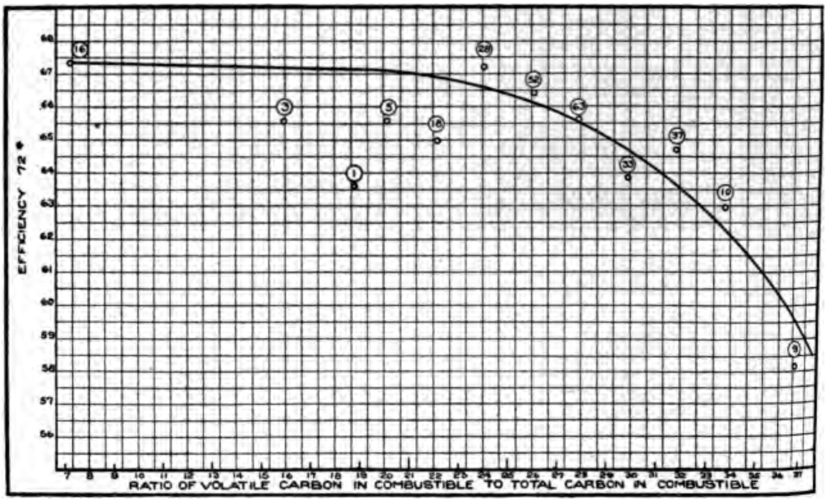


FIG. 48.—Relation between the ratio of volatile carbon to total carbon and efficiency 72*; tests 120-400.

Classifications have also been made on the following bases:

Per cent of sulphur from ultimate analysis of dry coal. (See fig. 28, p. 43.)
Per cent of ash in coal as fired. (See fig. 27, p. 41.)
Per cent of volatile matter in the "combustible." (See fig. 50, p. 89.)
Per cent of "fixed carbon," proximate analysis of coal as fired. (See fig. 51, p. 91.)
Per cent of free moisture, proximate analysis of coal as fired. (See fig. 22, p. 33.)
Per cent of ash, ultimate analysis of dry coal. (See fig. 26, p. 40.)
Per cent of oxygen in "combustible." (See fig. 52, p. 92.)
B. t. u. per pound of dry coal. (See fig. 53, p. 93.)

A study of the classifications of the ratios of carbon to hydro and hydrogen to available hydrogen and of single items from t proximate analysis of coal as fired and also the ultimate analysis dry coal reveals the fact that while the points determining the cur of efficiency 72* on the ratio bases fall rather uniformly on the curves, certain peculiarities are averaged out, as shown by the small variation of efficiency values over the entire range of the ratio. The classifications based on separate items from the chemical analysis of the coal give a much wider range of efficiency 72*.

The most valuable classification seems to be the one based on per cent of "fixed carbon" from the proximate analysis of the coal as fired.

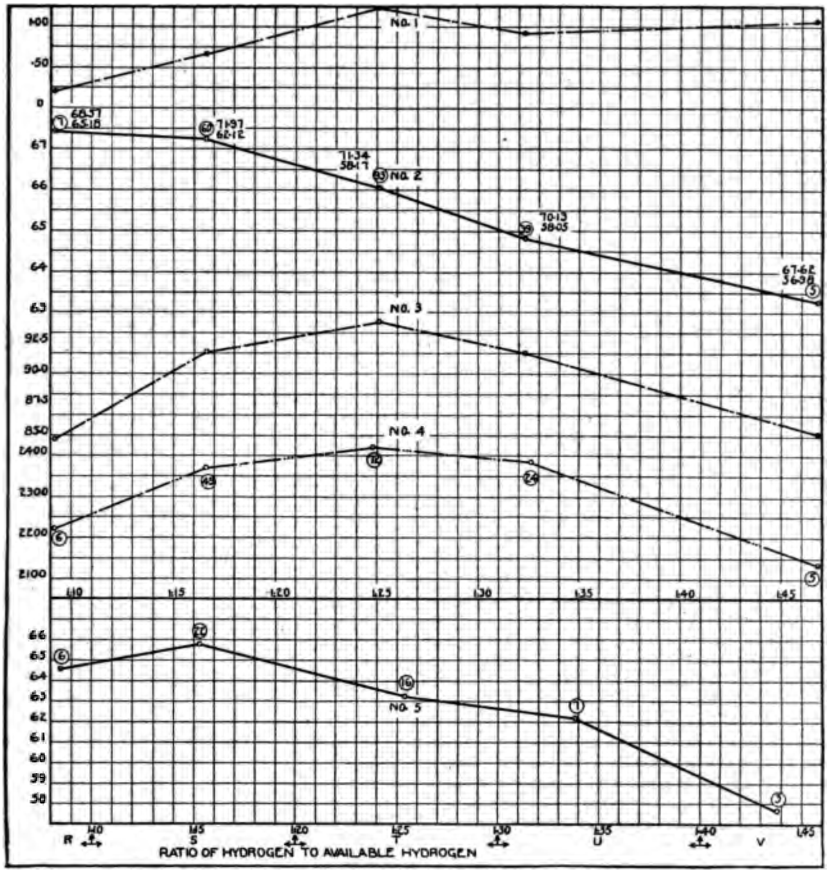


FIG. 49.—Coal classification based on ratio of hydrogen to available hydrogen as related to per cent of CO loss (curve No. 1); efficiency 72*, tests 124–380 (curve No. 2); per cent of rated capacity developed (curve No. 3); combustion-chamber temperature (°F.) (curve No. 4); and efficiency 72* (tests 1–78, excluding tests on washed and briquetted coals) (curve No. 5).

(See fig. 51.) A classification nearly as good, and giving a little larger range of efficiency is that based on per cent of "volatile matter" in the "combustible." (See fig. 50.) The practical value of a classification for estimating the efficiency 72* at which a coal can be burned depends largely on the ease with which the item on which the classification is based can be determined. Both per cent of "fixed carbon" and per cent of "volatile matter" are obtained from a proximate analysis of coal, which can be made with very little difficulty.

The reason for deciding on fixed carbon in coal as fired in preference to volatile matter in "combustible" was based on a comparison of the curves for combustion-chamber temperature on figs. 50 and 51. With the exception of the two end points, all the curves of fig. 51 are fairly regular.

The subjoined classification of efficiency 72* on a basis of carbon-hydrogen ratio in dry coal for varying ranges of combustion-chamber temperature is but a subdivision of the carbon-hydrogen averages shown on fig. 25 (p. 37). It was thought that for any single carbon-hydrogen ratio group the efficiency 72* might increase or decrease with an increase of combustion-chamber temperature. However, after the tests have been separated according to combustion-chamber temperatures there are so few points in each grouping that any conclusion would be unreliable.

The tabulation shows the familiar general relation of increase of efficiency 72* as the carbon-hydrogen ratio increases. Nothing else is shown.

Classification of efficiency 72 on basis of carbon-hydrogen ratio in dry coal.*

	Carbon-hydrogen ratio in dry coal.								
	13.5 to 14.	14 to 14.5.	14.5 to 15.	15 to 15.5.	15.5 to 16.	16 to 16.5.	16.5 to 17.	17 to 18.	18 up.
Temperature range 1,900° to 2,200° F.:									
Number of tests	8	3	4	6	1	4	2	2	7
Average carbon-hydrogen ratio in dry coal	13.75	14.33	14.83	15.17	15.55	16.31	16.67	17.48	20.39
Average efficiency 72*	63.85	63.61	66.16	64.36	65.95	64.18	67.18	68.18	67.56
Temperature range 2,200° to 2,300° F.:									
Number of tests	2	5	7	3	5	8	2	2	2
Average carbon-hydrogen ratio in dry coal	13.66	14.40	14.80	15.12	15.71	16.06	16.71	17.04	19.35
Average efficiency 72*	61.79	65.03	61.71	66.26	66.25	66.74	66.32	67.88	67.76
Temperature range 2,300° to 2,400° F.:									
Number of tests	2	12	6	7	5	4	1	....	4
Average carbon-hydrogeh ratio in dry coal	13.84	14.39	14.68	15.15	15.72	16.35	17.93	....	19.47
Average efficiency 72*	63.00	65.63	65.88	64.60	64.12	68.61	67.94	....	66.48
Temperature range 2,400° to 2,500° F.:									
Number of tests	3	6	5	11	6	10	2	....	2
Average carbon-hydrogen ratio in dry coal	13.78	14.42	14.81	15.16	15.70	16.29	16.67	....	20.42
Average efficiency 72*	61.62	63.83	66.61	66.00	66.13	67.61	64.59	....	66.84
Temperature range 2,500° to 2,600° F.:									
Number of tests	....	4	4	5	8	1	2	....	......
Average carbon-hydrogen ratio in dry coal	....	14.33	14.73	15.22	15.81	16.14	16.69	....	......
Average efficiency 72*	....	64.54	65.44	65.88	67.45	65.77	69.06	....	......
Temperature range 2,600° to 2,900° F.:									
Number of tests	....	2	9	4	7	....	2	....	......
Average carbon-hydrogen ratio in dry coal	....	14.31	14.75	15.24	15.68	....	16.64	....	......
Average efficiency 72*	....	62.35	64.96	63.33	68.64	....	68.77	....	......

PER CENT OF "VOLATILE MATTER" IN THE "COMBUSTIBLE."

The curves of fig. 50 are based on about 300 tests made on coals from all parts of the United States, classified according to the percentage of "volatile matter" in the "combustible," considering as "combustible" that portion of the coal which remains after taking out the moisture and ash as determined by the proximate analysis. As stated elsewhere the word "combustible" is really a misnomer.

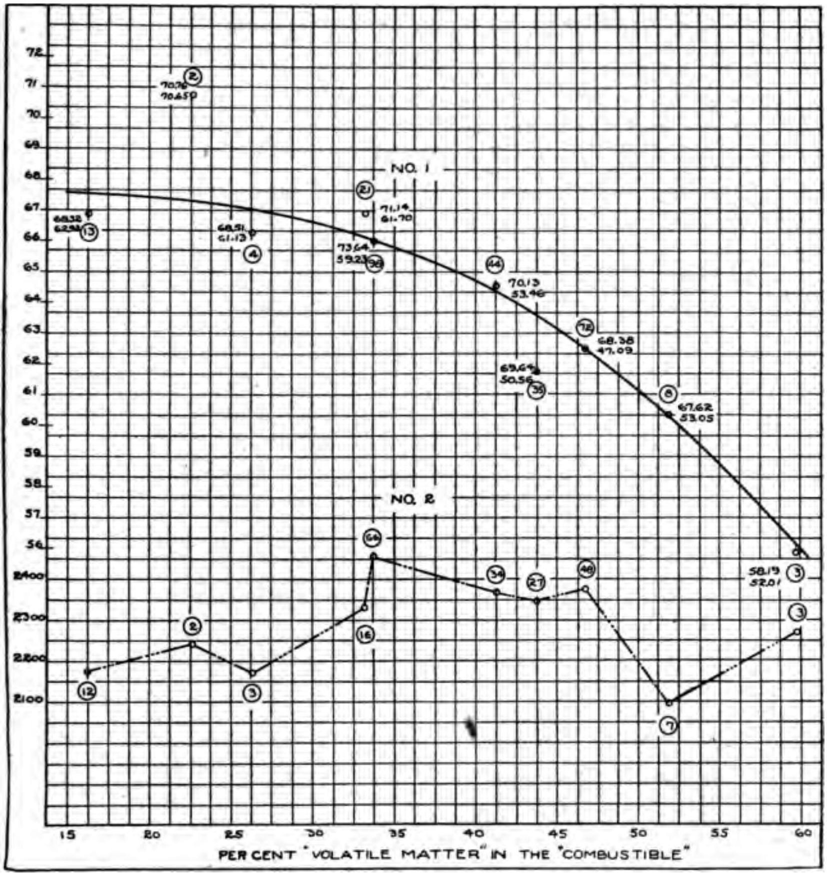


FIG. 50.—Relations of per cent of "volatile matter" in the "combustible" to efficiency 72* (curve No. 1) and combustion-chamber temperature (°F.) (curve No. 2). Tests 101-400.

The proximate analysis is also capable of considerable variation, but nevertheless it gives a clew.

Curve No. 1 is similar to many obtained by other investigators. It means that one should beware of a high percentage of "volatile matter," but not necessarily that a coal of high volatile matter is poor, for a great deal depends on the composition of the coal, inasmuch as coals break down very differently on heating. It has been noted that, in general, the coals of high volatile matter have some other undesirable features, such as high ash content. The most important thing to emphasize is that even with a good furnace the coals high in volatile matter are at a slight disadvantage.

Curve No. 2 shows that the combustion-chamber temperature rises with the volatile matter of coal up to about 38 per cent and then drops. The rise of the temperature is due to the fact that the volatile matter of the coal is driven off the fuel bed and burns in the combustion chamber, so that the temperature of the gases of combustion is measured before the heat is dissipated from them. The rise is also due to the increased rate of combustion. As the volatile matter increases the coal burns more rapidly and less air is used to burn 1 pound of combustible. Beyond 38 per cent of volatile matter the coals become high in ash and moisture; in fact all the lignites are classed among the coals at the right-hand end. Both the ash and moisture reduce the combustion-chamber temperature. The high ash causes a slower rate of combustion and consequently more air is used per pound of combustible. The moisture lowers the temperature directly by its high specific heat. Work on the constitution of the cellulose derivatives of coals, now being prosecuted at this plant and at several other places, should give some valuable information on such practical questions as these. The customary "proximate analysis" is only an empirical method and can be expected to give nothing more than clews; much more is to be expected from ultimate analyses.

As in all other curves of this bulletin the small numbers, by the points, indicate the number of tests and the four-place numbers indicate the highest and lowest efficiencies of each group.

FIXED CARBON (PROXIMATE ANALYSIS).

The chart shown in fig. 51 (p. 91) is one of a series based on the "proximate analysis" of "coal as fired." It is realized that such an analysis is purely empirical and capable of giving results varying considerably; nevertheless it is of some value.

Curve No. 1 shows a general rise of efficiency up to a "fixed carbon" content of 60 per cent and perhaps an inclination to fall off past that point. This 60 per cent point is roughly the place of maximum B. t. u. value per pound of moist coal. The numbers inclosed in circles show the number of tests falling in each group.

Curve No. 2, per cent of rated capacity developed, is practically uninfluenced.

Curve No. 3, combustion-chamber temperature, shows a general tendency to rise and has a hump in the middle. This is perhaps explained by the fact that the coals low in fixed carbon are of poor grade—high in ash and moisture—and for that reason it is difficult to get a hot fire with these coals. With coals high in fixed carbon nearly all of the combustion takes place in the fuel bed, so that the gases have cooled considerably by the time they reach the rear of the furnace. These coals also burn slowly and therefore require more air for combustion. The coals of moderate fixed carbon give a long, hot, luminous flame.

It is stated elsewhere in this bulletin that the capacity is a function of initial temperature of the furnace gases. This is plainly shown by curves Nos. 2 and 3, which are parallel.

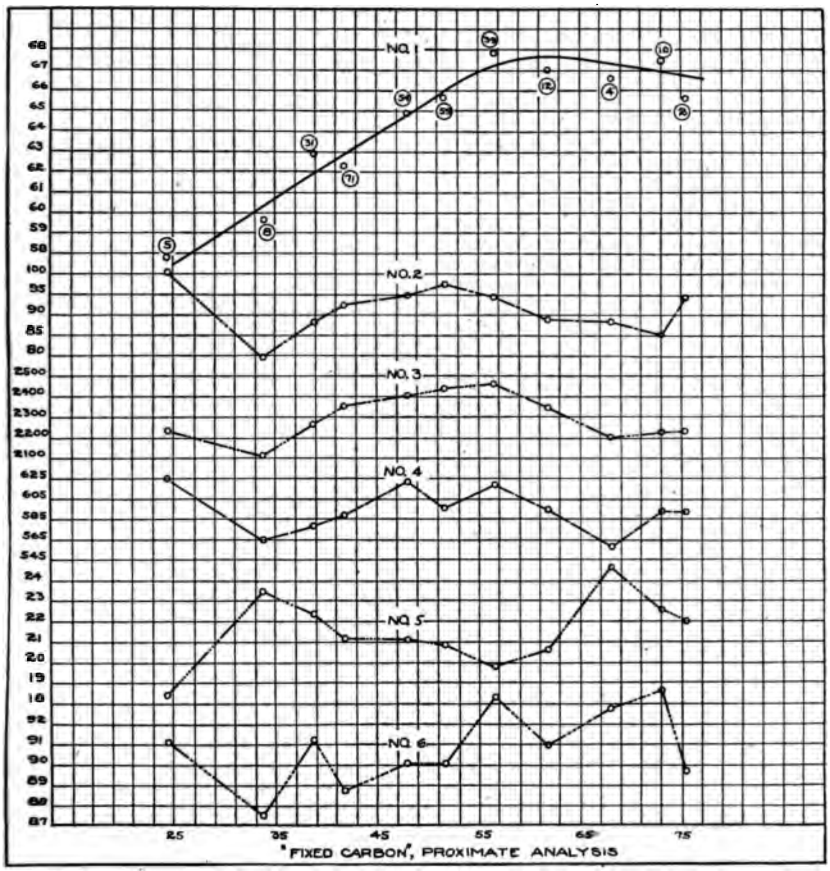


FIG. 51.—Relations of "fixed carbon" to efficiency 72* (curve No. 1); per cent of rated capacity developed (curve No. 2); combustion-chamber temperature (°F.) (curve No. 3); flue-gas temperature (°F.) (curve No. 4); pounds of dry chimney gases per pound of "combustible" (curve No. 5); and per cent completeness of combustion (E_3) (curve No. 6). Tests 89-401.

Curve No. 4, flue-gas temperature, is closely parallel to No. 3. This is only another illustration of the fact that with the boilers of this plant flue temperatures increase with furnace temperatures, and, so far as the authors can see, it must be so with all boilers, even when liberating the same quantity of heat in the furnace per second with various percentages of air excess. (See p. 24.)

Curve No. 5 shows the pounds of dry chimney gases per pound of "combustible." It is very little affected, tending to rise with the "fixed carbon." It varies inversely with furnace and flue temperatures.

Curve No. 6 shows the per cent of completeness of combustion, being the percentage of the heat of the combustible which was actually generated. It rises with increase of "fixed carbon" and its value of about 90 per cent indicates a wide margin for improvement.

RELATION OF EFFICIENCY 72* TO PER CENT OF OXYGEN IN "COMBUSTIBLE."

The chart shown in fig. 52 contains two curves plotted on the same data. The upper one was obtained by classifying the tests according to code "boiler efficiency" (72*) and the lower by classifying them according to the per cent of oxygen in the "combustible." By the "combustible" is meant what is left of the coal after taking out the moisture, sulphur, and ash. This remnant has been designated as "pure coal," which is preferable to calling it "combustible."

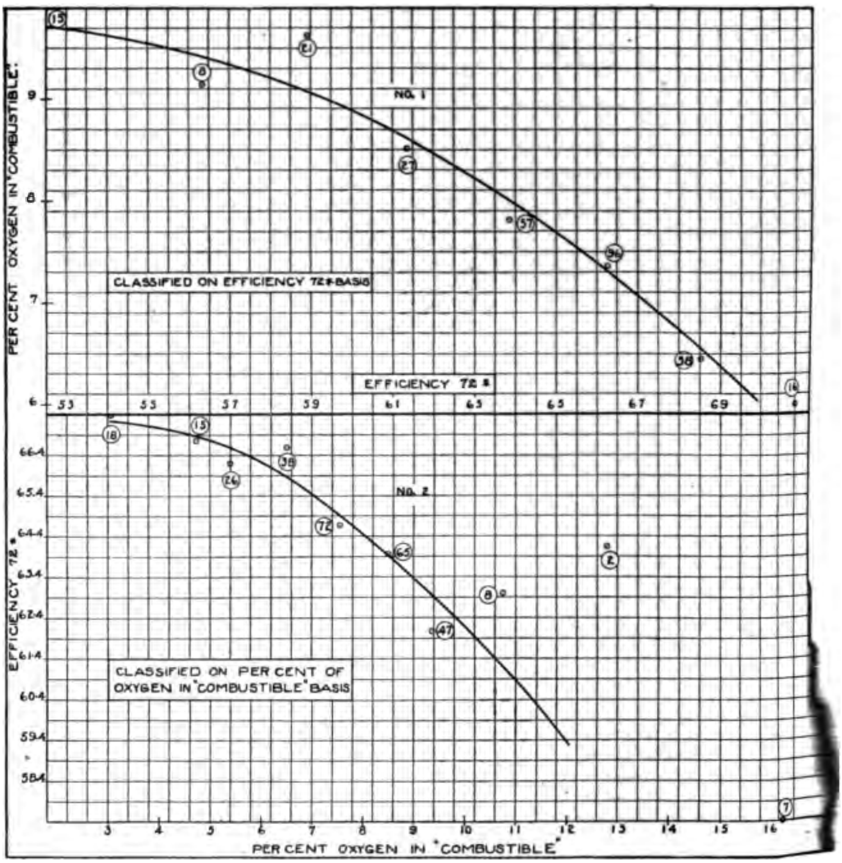


FIG. 52.—Relation of efficiency 72* to per cent of oxygen in "combustible," classified on each as a basis.
Tests 101-400.

Both curves show unmistakably that somehow the oxygen of the oal, which is chemically combined, exerts a harmful influence. It eems plausible that there is nothing inherent in the presence of oxyen in a coal molecule which makes it impossible to break it down nd burn it as well as any molecule lacking oxygen. This assumpion puts the blame on our furnaces.

This chart is in agreement with that of fig. 33 (p. 56), which preents a classification of several items on a smoke basis. The "unacounted-for" loss, CO loss, and per cent of oxygen all rise with the ncrease of smoke and the efficiency falls very slightly.

BRITISH THERMAL UNITS PER POUND OF DRY COAL.

The curves of fig. 53 are based on 296 tests made on coals from ll parts of the country. In general, the eastern coals fall on the

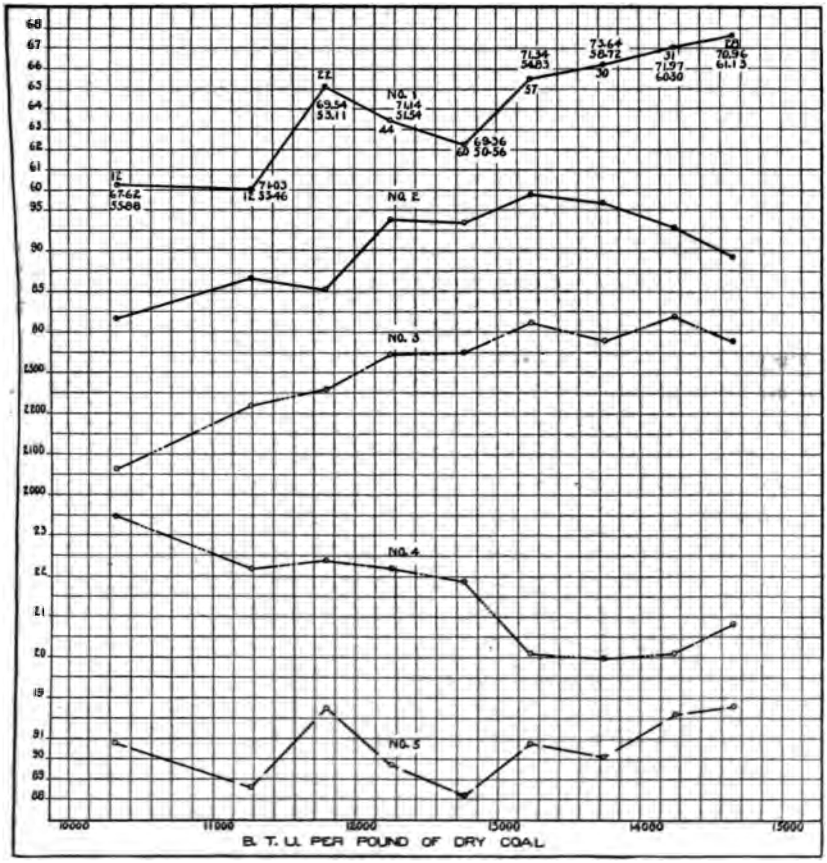


FIG. 53.—Relations of B. t. u. value of dry coal to boiler efficiency 72* (curve No. 1); per cent rated capacity developed (curve No. 2); combustion-chamber temperature (° F.) (curve No. 3); pounds of dry chimney gases per pound of "combustible" (curve No. 4); per cent completeness of combustion (E_3) (curve No. 5). Tests 80-400.

right and the lignites on the left part of the curve. On curve No. 1 the small number near each point gives the number of tests falling in that B. t. u. group. Each of the other four curves below is based on the same number of tests in the various groups. The four-place numbers in pairs on curve No. 1 indicate the highest and lowest efficiencies 72* falling in each group. It will be noted that the highest efficiencies are nearly as good in the left groups as in the right, indicating that it is possible to burn coals of low heating value as efficiently as high-grade coals. The increase of average efficiencies is only about 7 per cent for the range of 5,000 B. t. u.

The average capacity, as shown by curve No. 2, rises considerably as the coal improves in heating value. Perhaps most of the low B. t. u. coals could be made to furnish as much steam if burned on a larger grate. If the coal did not clinker seriously, the use of a rocking grate would increase the capacity. On some coals the use of the automatic stoker might give better results.

Curve No. 4, pounds of dry chimney gases per pound of "combustible," descends with the better coals, partly because they are usually more manageable on the fuel bed and because they seem to break down on heating with evolution of gaseous compounds easier to burn, on which account the air supply can be reduced with safety.

Curve No. 5 gives the average "furnace efficiency," or, better, the per cent of completeness of combustion. These calculated efficiencies are only approximate.

RATIO OF ASH TO SULPHUR IN DRY COAL.

It is sometimes said that although sulphur in coal does not of itself materially reduce the value of the coal for steam making, a low percentage of ash with a high percentage of sulphur is apt to make trouble. To test this possibility a classification was made of many tests on many coals, the tests being grouped according to the ratio of total ash to sulphur. The corresponding values of the averages of efficiencies 72* are practically constant.

As a check on this work a classification was also made of the ratio of ash to sulphur in dry coal on an efficiency 72* basis. As the efficiency 72* increases there is practically no change in the value of the ash to sulphur ratio. (See figs. 21, p. 30, and 28, p. 43.)

A table of efficiencies 72* classified on the basis of per cent of ash plus sulphur in dry coal shows little variation between the average efficiency values for the several groups. Tables showing the three classifications follow:

Classification of efficiency 72 on basis of ratio of ash to sulphur in dry coal.*

	Ratio of ash to sulphur.								
	0 to 2.5.	2.5 to 5.0.	5.0 to 7.5.	7.5 to 10.	10 to 15.	15 to 20.	20 to 25.	25 to 30.	Over 30.
Number of tests	27	106	73	27	8	17	9	4	4
Average ratio of ash to sulphur	2.23	3.39	6.06	8.69	12.10	17.11	22.64	26.46	33.29
Average efficiency 72*	64.83	64.57	66.45	66.09	65.76	64.67	64.96	65.98	66.26

Classification of ratio of ash to sulphur in dry coal on basis of efficiency 72.*

	Efficiency 72*.											
	Up to 53.	53 to 57.	57 to 59.	59 to 62.	62 to 63.	63 to 64.	64 to 65.	65 to 66.	66 to 67.	67 to 68.	68 to 69.	69 and over.
Number of tests	1	5	12	26	15	19	28	43	32	36	25	34
Average efficiency 72*	52.01	55.49	58.20	60.62	62.49	63.45	64.44	65.54	66.41	67.47	68.38	70.18
Average ratio of ash to sulphur in dry coal	16.27	6.24	5.77	6.61	4.40	7.67	4.81	8.82	6.31	7.30	6.51	8.64

Classification of efficiency 72 on per cent of ash plus sulphur in dry coal (Indiana, Illinois, and western Kentucky coals).*

	Per cent of ash plus sulphur.								
	Up to 9.	9 to 11.	11 to 13.	13 to 15.	15 to 17.	17 to 19.	19 to 21.	21 to 23.	23 up.
Number of tests	3	13	7	16	14	14	8	12	5
Average per cent of ash plus sulphur in dry coal	7.40	10.38	11.95	14.14	15.98	18.12	20.02	21.90	24.83
Average efficiency 72*	66.00	65.73	68.03	63.44	64.73	64.10	65.47	66.33	66.47

SUGGESTED STEAM-TURBINE CYCLES, HEAT ABSORPTION, AND BOILER EFFICIENCIES.

THE BOILER AND THE FURNACE AND THEIR EFFICIENCIES.

The boiler with its setting consists mainly of two parts, the furnace and the boiler proper. The furnace is the heat generator and the boiler the heat absorber. In practice both are imperfect in their functions. A perfect furnace would burn the fuel completely. A perfect boiler would absorb all the heat evolved in the furnace provided the temperature of the water in the boiler was that of the atmosphere. It follows, then, that the furnace efficiency is the ratio of the heat evolved in the furnace to the potential heat of the fuel fired, and that the boiler efficiency is the ratio of the heat absorbed by the boiler to the heat evolved in the furnace; the combined efficiency of the furnace and boiler being the ratio of the heat absorbed by the boiler to the potential heat of the fuel fired. The grate is taken as a part of the furnace. The true boiler efficiency is the ratio of the heat absorbed to the heat which is available to the boiler, this available heat being that portion of the heat in the furnace gases which is above the temperature of the steam.

If the wording in the above definitions is somewhat changed another set of efficiencies is obtained, which may be called the thermodynamic efficiencies. The efficiency of the furnace is the ratio of the heat made available to the boiler to the potential heat of the fuel fired. The efficiency of the boiler is the ratio of that portion of the heat absorbed which is available for power purposes (engine or turbine) to the heat available to the boiler. The combined efficiency of the furnace and boiler is the ratio of the heat made available for power purposes to the heat value of the fuel fired. The fact is that the steam engine is usually blamed for wasting heat which is not available to it.

To illustrate the above definitions let the various heat values be represented by diagrams. For the representation of the heat in the furnace a diagram such as given in *A*, fig. 54, can be used. This diagram has absolute temperature for the ordinates, and a factor proportional to the specific heat of the furnace gases multiplied by their weight as abscissas. In the same chart (fig. 54, *B*) is an ideal cycle of a steam engine or turbine plotted on temperature-entropy plane. It must be understood that the abscissas of these two diagrams are in different units. The abscissa in *B* is taken in entropy units because the adiabatic expansion and the availability of heat to the steam engine or turbine can be best shown by temperature-entropy diagrams.

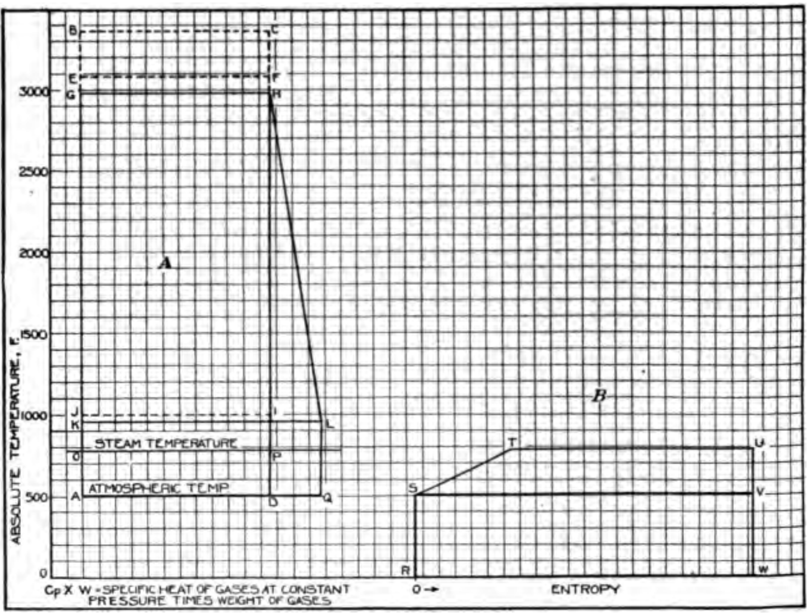


FIG. 54.—Temperature-entropy diagrams for boiler: *A*, For air and coal; *B*, for water and steam.

On the assumption that 1 pound of combustible is completely burned, the various quantities of heat in the furnace are represented in *A* as follows: The area ABCD represents the potential heat in the fuel and also the heat developed in the furnace. The heat available for the boiler, represented in the diagram by the area OBCP, is the heat above the temperature of the steam and is the limit of the heat which the boiler can absorb. The remainder of the heat, represented by the area AOPD, is below the temperature of the steam and therefore can not be absorbed by the boiler.

In *B* the area RSTUW represents the heat absorbed by the boiler and delivered to the engine. Of this heat only a portion, represented by the area STUV, is available for the engine to be converted into mechanical energy. The remainder of the heat, represented by the area RSVW, is below the atmospheric temperature and can not be converted by the steam engine into mechanical energy. It may be said here that the limit for adiabatic expansion of steam in a steam engine or turbine is set by the temperature of the cooling water in the condenser. However, as the cooling water is nearly at the temperature of the atmosphere, the atmospheric temperature may be taken as the limit. It is entirely out of the question to obtain lower pressure in a condenser than that corresponding to the steam temperature equal to the temperature of the cooling water, no matter how perfect the air pump may be. For this reason it is said that the heat which is left in steam after it has been expanded adiabatically to the temperature of the atmosphere is below the atmospheric temperature. Of course this reasoning does not apply to a case where the steam is used for heating purposes.

During the process of transmitting the heat from the boiler furnace to the engine, the heat loses much of its availability, the greatest drop being in the transmission of the heat from the furnace gases into the boiler water. During this transmission there is a great drop in temperature, and with it drops the availability.

To show what efficiency could be obtained from an ideal steam-generating outfit and a steam engine working on a perfect cycle, as shown in *B*, fig. 54, an example is given below:

Suppose that 1 pound of "combustible" of the coal of test No. 204 is burned with 18.3 pounds of air in a perfect furnace. The heat value of 1 pound of this "combustible" is 14,660 B. t. u.; and if we assume the atmospheric temperature to be 50° F. and the steam pressure 80 pounds by gage, the various heat quantities are as follows: Heat evolved in furnace, 14,660 B. t. u.; heat available for boiler, 13,320 B. t. u. The remaining portion of the heat evolved in the furnace is below 324° F., the temperature of the steam, and is either in the gases or in the moisture formed by burning the hydrogen of the "combustible." As this is an ideal case, all the heat which is available to the boiler is absorbed by it. On the assumption that there is no radiation from the boiler and the pipe connections, the heat delivered to the engine is 13,320 B. t. u. Of this heat only 4,056 B. t. u. is available for the engine. This last quantity can be obtained from a steam table (such as Reeve's) in the following manner:

The total heat of 1 pound of saturated steam at 80 pounds gage pressure is 1,180.3 B. t. u., and the entropy is 1.5976. Within the limit this steam can be expanded to atmospheric temperature, which in this assumed case is 50° F. The corresponding absolute pressure of steam is given in the table as 0.36 inch of mercury. The total heat of 1 pound of steam at this pressure is 1,096.8 B. t. u. and the entropy 2.1478. The heat of 1 pound of water at 50° F. is 18.08 B. t. u., and the entropy is 0.0360 in the table, the heats and entropies being counted from feed water at 32° F.

As the temperature of the feed water is nearly that of the atmosphere, which in the assumed case is 50° F., the heats and entropies used in this problem are counted from feed water at 50° F. These heats and entropies can be obtained by subtracting from the values given in the table the heat and entropy of water at 50° F. Inasmuch as with adiabatic expansion the entropy remains constant, the quality of the steam at the end of the expansion of steam from 80 pounds gage to 0.36 inch of mercury absolute pressure is:

$$\frac{1.5976-.0360}{2.1478-.0360}=\frac{1.5616}{2.1118}=74 \text{ per cent dry.}$$

The heat left in 1 pound of steam at the end of the expansion is

$$(1{,}096.8-18.08)\times .74=797.1.$$

The total heat left in the steam at the end of the expansion when $\frac{13{,}320}{1{,}180.3-18.08}$ pounds of steam is used is

$$\frac{13{,}320}{1{,}180.3-18.08}\times 797.1=9{,}264.1.$$

Then the heat converted into work is 13,320 – 9,264.1 = 4,056 B. t. u. In this case the heat in the condensed steam does not enter into the computation because it is at the temperature of the feed water.

In the example just given the various efficiencies are as follows: Furnace efficiency = 14,660 ÷ 14,660 = 100 per cent; boiler efficiency = 13,320 ÷ 14,660 = 90.9 per cent; boiler and furnace efficiency = 13,320 ÷ 14,660 = 90.9 per cent; true boiler efficiency = 13,320 ÷ 13,320 = 100 per cent. The thermodynamic efficiencies are: Furnace efficiency = 13,320 ÷ 14,660 = 90.9 per cent; boiler efficiency = 4,056 ÷ 13,320 = 30.45 per cent; efficiency of furnace and boiler = 4,056 ÷ 14,660 = 27.67 per cent.

Of course by means of the economizer and by using superheated steam these ideal efficiencies could be somewhat raised. Steam boilers are not as efficient for power purposes as the figures obtained from boiler trials ordinarily imply.

In the above discussion only the limiting case was considered. In practice there are many losses which reduce the boiler efficiency to less than two-thirds and the total efficiency of the steam outfit to less than one-half.

As the process of heat evolution and heat transmission goes on in the furnace and the boiler the principal sources of loss are about as follows:

(*a*) Part of the combustible drops through the grate into the ash pit and is not burned.

(*b*) Part of the coal is gasified, and the gases escape before they are burned.

(*c*) Part of the heat evolved in the furnace is radiated through the fire doors and the furnace walls.

Of these three losses, the second is perhaps the most serious and increases rapidly after the content of CO_2 in the flue gases passes a certain limit. (See fig. 31, p. 51.) Losses *a* and *b* diminish the heat which is actually evolved in the furnace, and the temperature of the gases of combustion. In fig. 54 these losses are represented by the area EBCF. Loss *c* further decreases the heat which has already been evolved in the furnace. In the diagram this loss of heat is represented by the area GEFH.

(*d*) No boiler cools the furnace gases to the temperature of the steam; the gases leave the heating surface of the boiler at a temperature from 100° to 300° F. higher than that of the steam. The heat lost in the waste gases is represented by the area AJID.

(*e*) As the gases pass through the boiler setting cold air leaks in, lowers their temperature, and by increasing their weight increases the loss up the stack. The heat loss in the waste gases is then represented by the area AKLQ, and the loss due to the leakage of air is represented by the difference of the areas AKLQ and AJID.

(*f*) The total moisture (from the coal and air, the water of composition, and the moisture formed by the burning of the available hydrogen of the coal) lowers the temperature of combustion and with its high specific and latent heat increases the loss up the stack.

The heat value of the coal is represented by the total area ABCD, the heat actually evolved in the furnace by the area AEFD, the heat available to the boiler by the area JGHI, and the heat absorbed by the boiler, if there were no leakage of air, by the area JGHI. When air leaks into the setting the heat absorbed by the boiler is represented by the difference between the area AGHD and the area AKLQ.

In most of the commercial appliances for making steam the process of heat absorption begins before the process of heat evolution has been completed; in fact, the two processes go on together as soon as the temperature of the gases has risen sufficiently above the temperature of the steam. This is true to a great extent with all furnaces having no clay-tile roof and no combustion chamber and with all internally fired boilers. Even in a furnace of the Heine type a considerable portion of the heat is absorbed by the boiler through the tile roof. Such abstraction of heat necessarily reduces the final temperature of the products of combustion.

HIGH INITIAL FURNACE TEMPERATURE AND ITS EFFECT ON ECONOMY.

From what is said in the paragraphs on efficiencies it appears that more heat can be made available for the boiler if higher initial temperature and lower steam pressure be used. In general this proposition is true; however, both conditions have their limits beyond which new losses coming into play more than counterbalance the gain.

First let the relative gain and loss due to high initial temperature be considered. In order to obtain high initial temperature it is necessary to reduce the weight of gases per pound of "combustible." This condition means that less air is admitted into the furnace and less free oxygen is present in the gases. The reduction of free oxygen in the gases necessarily increases the amount of incomplete combustion, as shown in figs. 13 (p. 22), 14 (p. 23), and 31 (p. 51). The curve of fig. 31 indicates that the furnace efficiency drops very rapidly after the CO_2 content in the flue gas has reached about 9 per cent (perhaps 11 or 12 per cent in the furnace, before the gases have been diluted by leaks).

The loss up the stack is not reduced so much as the reduction of the weight of the gases per pound of "combustible" would indicate, because with the rise of the initial temperature the flue-gas temperature also rises. The curve of fig. 16 (p. 24) shows this relation of the flue-gas temperature to the initial (combustion-chamber) temperature.

To show that extremes either in high or low initial temperature may reduce the combined efficiency of the furnace and boiler, three cases were computed, and the results are given on page 101.

Suppose that the coal of test 204 is burned with three different furnace-gas compositions, having CO_2 contents of 7.0, 10.0, and 13.0 per cent, the respective percentages of completeness of combustion as obtained from the curve of fig. 31 will be 91.8, 90.5, and 86.4 per cent. To account for the loss in incomplete combustion the flue-gas analyses might be about as given below:

Hypothetical flue-gas analyses.

Gas.	Case 1.	Case 2.	Case 3.
CO_2	7.0	10.0	13.0
O_2	12.0	8.0	5.0
CO	.2	.4	1.0
CH_4	.15	.2	.4
H_2	.1	.2	.3
C_2H_4	.05	.1	.2
N_2	80.5	81.1	80.1
	100.00	100.0	100.0

Except perhaps CO, all the combustible gases in all three cases are by ordinary methods undeterminable; it is simply assumed that they are present. The heat loss due to each combustible gas in the assumed composition of flue gases is computed by the following general formulas:

(*a*) Loss due to CO =

$$\frac{28\text{CO}}{12\ (\text{CO}_2+\text{CO}+\text{CH}_4+2\text{C}_2\text{H}_4)}\times\left\{\begin{matrix}\text{per cent of carbon}\\ \text{in ``combustible''}\end{matrix}\right\}\times 4{,}325.$$

(*b*) Loss due to CH_4 =

$$\frac{16\text{CH}_4}{12\ (\text{CO}_2+\text{CO}+\text{CH}_4+2\text{C}_2\text{H}_4)}\times\left\{\begin{matrix}\text{per cent of carbon}\\ \text{in ``combustible''}\end{matrix}\right\}\times 23{,}510.$$

(*c*) Loss due to H_2 =

$$\frac{2\text{H}_2}{12\ (\text{CO}_2+\text{CO}+\text{CH}_4+2\text{C}_2\text{H}_4)}\times\left\{\begin{matrix}\text{per cent of carbon}\\ \text{in ``combustible''}\end{matrix}\right\}\times 62{,}030.$$

(*d*) Loss due to C_2H_4 =

$$\frac{28\text{C}_2\text{H}_4}{12\ (\text{CO}_2+\text{CO}+\text{CH}_4+2\text{C}_2\text{H}_4)}\times\left\{\begin{matrix}\text{per cent of carbon}\\ \text{in ``combustible''}\end{matrix}\right\}\times 21{,}340.$$

The number at the end of each formula is the heat value of 1 pound of that particular gas. The results obtained are in B. t. u.

The loss due to the presence of each gas in each of the three cases, together with the calculated results, is shown below.

Calculated losses and results due to the presence of combustible gases in the flue gases in the three cases (steam pressure taken to be 80 pounds gage).

	Case 1.	Case 2.	Case 3.
Loss due to —			
CO	227	313	572
CH_4	529	487	710
H_2	116	160	176
C_2H_4	280	387	564
Total loss	1,152	1,347	2,022
Calculated results:			
Heat value of 1 pound of "combustible" ... B. t. u.	14.660	14,660	14,660
Heat evolved in furnace ... do.	13,460	13,270	12,670
Dry gas per pound of "combustible" ... pounds.	14.23	19.3	27.71
Water vapor per pound of "combustible" ... do.	0.5887	0.5887	0.5887
Temperature of product of combustion (if completeness of combustion were 100 per cent) ... °F[a].	2,075	2,906	3.850
Probable completeness of combustion ... per cent.	91.8	90.5	86.4
Probable temperature of products of combustion ... °F.	1,903	2,624	3,310
Probable flue-gas temperature ... do.	543	598	639
Heat absorbed by boiler ... B. t. u.	9,424	10,053	9,875
Boiler efficiency	69.9	75.9	77.8
Over-all efficiency	64.2	68.7	67.3

[a] Specific heats assumed to be constant.

The diagrams giving the representation of the various quantities of heat of the three cases discussed are presented in fig. 55. Each of the areas ABCD is the potential heat in the coal; the areas BCFE are the incomplete combustion losses; each of the areas AEFD is the heat actually evolved in the furnace. Of the heat evolved in the furnace only the area GEFH in each diagram is the heat absorbed by the boiler. The minor losses are not represented in detail.

The over-all efficiency indicates that it is better to burn the coal with the initial temperature given in case II than with the high initial temperature given in case III, although the latter gives much better results than the low temperature in case I. On account of the increased radiation at high temperature, the actual results in case III might not show so much advantage over case I as the calculated results.

Another disadvantage of high initial temperature is the deterioration of the furnace. When high furnace temperatures are used the bridge wall has to be rebuilt often and the side walls lined. A hot fuel bed melts the refuse on the grate and causes the formation of clinkers. Hot clinker warps and destroys the grate bars, besides making the fires very hard to clean and disturbing the evenness of the air supply through the fuel bed.

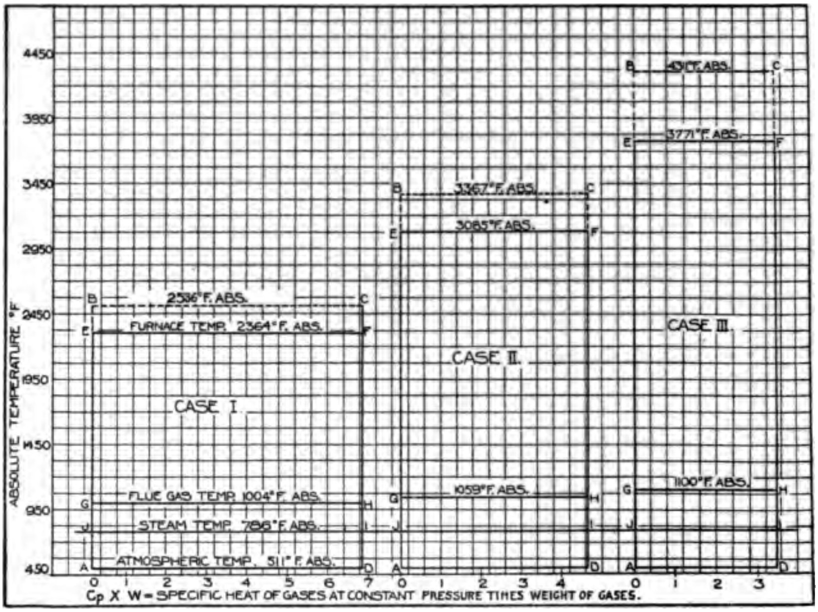


FIG. 55.—Availability to a boiler of heat of combustion of carbon in three different cases.

Fig. 17 shows that in general the capacity of the boiler increases as the combustion-chamber or initial temperature rises. The advantages and disadvantages of high initial temperature may be summarized as follows: Advantages—(*a*) Increase in boiler efficiency; (*b*) increase in capacity. Disadvantages—(*a*) More loss by incomplete combustion; (*b*) increased radiation; (*c*) deterioration of furnace.

LOW STEAM PRESSURE AND ITS EFFECT ON ECONOMY.

It has been said that more heat could be made available and more heat would be absorbed by the boiler if lower steam pressure were used. For power purposes, however, the gain in boiler efficiency ould be more than offset by the loss in availability of the heat for he engine. If, however, the steam at low pressure be highly supereated and used in a steam turbine specially designed, an increase of to 4 per cent in the thermodynamic efficiency of the outfit might be xpected.

In the following paragraph is a conservative computation of the robable increase of the efficiencies of a boiler and a steam turbine esulting from the reduction of steam pressure and the superheating f the steam. In the computation of the steam-turbine efficiencies t has been assumed that the friction of the steam through the nozzles nd the turbine blades would decrease as the pressure dropped, and hat the expansion of the steam would therefore be more nearly diabatic. This reduction of friction can be reasonably expected, ecause the friction of fluids against a solid increases directly as the ensity of the fluid. Furthermore, the expansion of highly supereated steam at low pressure will take place entirely in the supereated region, and thus friction due to condensed steam, which is a erious item in steam turbines as ordinarily built and operated, will be avoided.

Let four cases be considered—case 4, gage pressure 200 pounds, superheat 200° to 587.5° F.; case 3, gage pressure 100 pounds, superheat to 800° F.; case 2, gage pressure 25 pounds, superheat to 800° F.; case 1, gage pressure 15 pounds, superheat to 800° F.; temperature of feed water, 82° F.; condenser vacuum, 1.2 pounds absolute pressure (28 inches mercury below an atmospheric pressure of 14.7 pounds). Assume the coal of test 204 to be burned with the resulting product of combustion equal to 19.3 pounds of dry chimney gases per pound of "combustible." The heat in chimney gases per 1° F. per pound of combustible is, in dry gases, $19.3 \times 0.24 = 4.63$ B. t. u.; in moisture, $0.5887 \times 0.48 = 0.28$ B. t. u.; total, 4.91 B. t. u. The heating value of 1 pound of combustible is 14,660 B. t. u. About 83 per cent of the increase in the heat available for the boiler due to the drop of steam temperature will be absorbed (the true boiler efficiency being taken at about 83 per cent).

Calculated increase of boiler efficiency due to drop in steam temperature.

	Drop of steam pressure (pounds) from 200 to—		
	100.	25.	15.
Heat taken out of flue gases due to drop of steam temperature B. t. u.	244	491	564
Probable increase in boiler efficiency, per cent	1.66	3.35	3.85

This increase in boiler efficiency may seem small. However, the great reduction of the first cost of installation of a plant makes the reduction in steam pressure appear more practicable—for instance, multitubular boilers would then be as safe as water-tube boilers. Further, 83 per cent true boiler efficiency should be far surpassed in the future.

Quantities used in calculation and probable results of the use of steam of low pressure and high superheat in steam turbines.

	Case 1.	Case 2.	Case 3.	Case 4.
Steam pressure by gage............pounds..	15	25	100	200
Steam pressure, absolute............do..	29.7	39.7	114.7	214.7
Temperature of saturated steam............°F..	249.5	267.0	327.0	387.5
Temperature of superheated steam............do..	800	800	800	587.5
Temperature of superheated steam, absolute............do..	1,260.8	1,260.8	1260.8	1,048.3
Total heat of superheated steam above 82 °F. (λ_1) ...B. t. u..	1,372.5	1,369.0	1357.0	1,245.0
Total heat in steam at 28-inch vacuum above 82 °F. (λ_2)..do..	1,035	1,031	978	888
$\lambda_1-\lambda_2$............do..	337.5	338	379	357
Assumed coefficient of friction of steam in nozzle and blades (see p. 103)............	0.10	0.12	0.24	0.30
Coefficient of friction calculated from the law of friction of fluids, assuming the one in case 4 to be 0.3............	0.084	0.10	0.22	....
Heat converted into work, H_w, calculated with the assumed coefficient of friction............	303.0	297.5	288.0	250.0
Thermodynamic efficiency of steam turbine............	22.1	21.7	21.2	20.1
Over-all efficiency of steam-generating outfit............	68.85	68.35	66.66	65.0
Combined thermodynamic efficiency of boiler and turbine....	15.2	14.8	14.1	13.1
Gain in combined thermodynamic efficiency of boiler and turbine over case 4............	16.1	13.0	7.6	....

The coefficient of friction of steam in nozzles and blades was assumed to be 0.3 for case 4, which is in close agreement with practice. The coefficients of friction for the other three cases were taken somewhat larger than those calculated from the law of friction of fluids, in order to be safe.

The over-all efficiency of a steam-generating outfit in case 4 was assumed to be 65.0, which can be attained in a well-operated boiler room. The over-all boiler efficiencies in the other three cases were obtained by adding to 65 the increase in efficiency as calculated in the preceding paragraphs.

Fig. 56 shows the cycle of thermodynamic processes of each of the four cases. In the chart the subscripts 1, 2, 3, and 4 of the letters refer to cases 1, 2, 3, and 4, respectively; letters having no subscripts are applicable to all cases.

Take case 4 for example: The area under AB_4 represents the sensible heat of the water, the area under B_4C_4 the latent heat of steam, and the area under C_4D_4 the heat in the steam due to superheat at constant pressure; the total heat in the superheated steam as it reaches the steam turbine is then represented by the area under $AB_4C_4D_4$. If there were no friction of steam during the expansion in the steam nozzle and the blades the expansion would be purely adiabatic, and in the diagram it would be represented by a vertical line from the point D_4. However, since friction comes into play during the expansion and changes part of the velocity of steam back into heat, the expansion is a combination of the processes of adiabatic expansion and heating at constant pressure, and is represented on the chart by the curve D_4F_4. The heat rejected to the condenser is the heat under AEF_4. In cases 1 and 2 the heat rejected is the heat under $AEHF_1$ and $AEHF_2$, respectively, since the steam reaches the condenser in a slightly superheated state. The difference between the heat delivered to the turbine and the heat rejected to the condenser is the heat which has been transformed into the velocity of steam which is represented by the area under $AB_4C_4D_4$ minus the area under AEF_4. It must be understood that the heat changed into motion is not represented by the area inclosed by $EB_4C_4D_4F_4$.

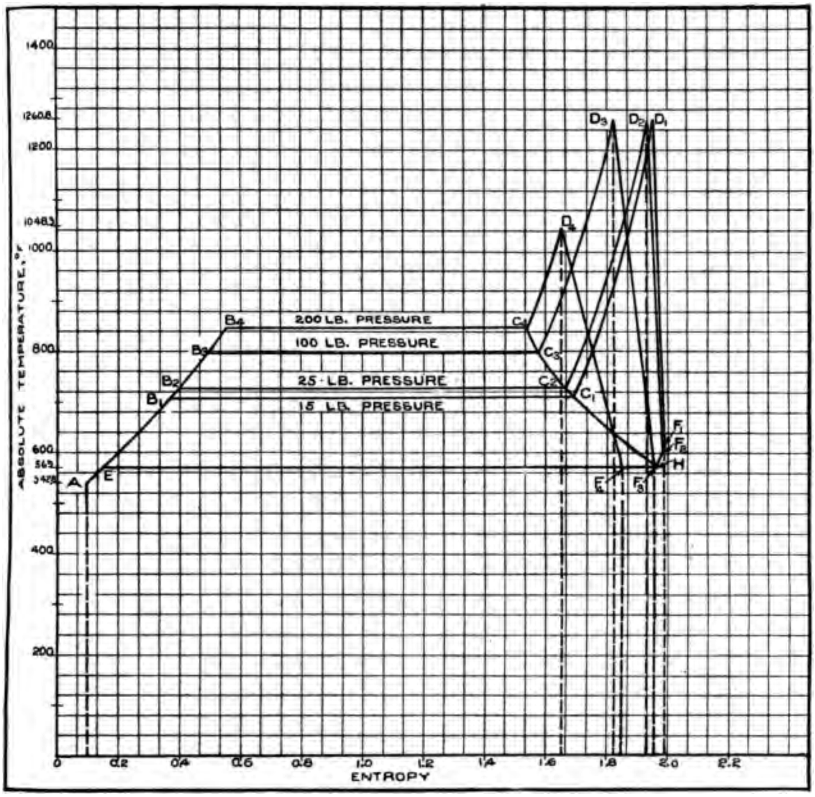


FIG. 56.—Temperature-entropy diagrams for steam-turbine cycles.

HEAT TRANSMISSION THROUGH BOILER TUBES, AND TRUE BOILER AND FURNACE EFFICIENCIES.

From the very start of the steaming tests those conducting them sought to separate the performance of the boiler as a heat absorber from the performance of the fuel bed and furnace as a heat producer. In writing up the stages through which opinions progressed it seems best to adopt the historical method and outline all attempts, up to the last calculations, which are both theoretical and practical, being determined from about 400 tests. This last work must be taken as neither final nor even necessarily correct; it is simply the best we know at present. All opinions expressed or deductions drawn must be understood as merely tentative, and the right is reserved to change part or all of them at any future time.

The first definite calculations on boiler efficiency were made in January, 1906, in an attempt to check the temperature indications of a Wanner optical pyrometer, which had been used to ascertain the temperatures in the rear of the combustion chamber. Sometimes the observation was taken by looking at flame, in which case it was postulated that the flames of various coals differ in brightness at the same temperature; and, perhaps, although the particles of incandescent carbon from which the pyrometer received its light were really at the temperature as read off the scale, such a likely condition was no assurance that the molecules of gas between were as hot; the reasonable assumption would be that they were cooler. Or, worse yet, when a coal and the conditions of a test were such as to give short flames, or none, in the rear of the combustion chamber, and the pyrometer received its light from the opposite side wall, it was plainly evident on observation that the temperature as read from the instrument was too low, because the side wall was cooler than the tile furnace roof, on account of its radiating heat to the bare water tubes near by, which the tile roof could not do. Even the tiles of the roof were conducting heat through to the tubes which they protected. These and other considerations put the indications of the optical pyrometer in question, through no fault of its own. Attempts were made to check the pyrometer with a platinum and platinum-rhodium thermoelectric couple, but the porcelain tubes slagged and melted away within an hour or so under the high temperatures used, and a satisfactory protection for the junction was not made to work reliably until too late for this purpose. By this time it had been learned that the ascertainment of the temperature of the gases entering the boiler was not, after all, of such overwhelming importance. So this tedious checking of the optical pyrometer was dropped for more fruitful work. There is a general impression among the observers that the pyrometer when used on such furnaces as these is usually correct within 50° C. or 100° F. (For a description of the method of protecting the thermoelectric couple with a water jacket and cheap clay pipestems see p. 54.)

These calculations on boiler efficiency were made because an attempt to obtain any curve of relationship between combustion-chamber temperatures (obtained by the Wanner optical pyrometer) and over-all efficiency of the furnace and boiler combined resulted in a failure, the points falling all over the sheet of coordinate paper. At that time the impression of the staff was that the following formula applied to boilers as well as to condensers, and so it does, but that is only one-third of the story:

Efficiency of boiler as a heat absorber $= \frac{t_1 - t_2}{t_1}$ where t_1 = initial temperature of gases above atmosphere, and t_2 = final temperature of gases above atmosphere.

Many of the staff believed at that time that if the air supply per pound of coal were reduced, without decreasing the completeness of combustion (in consequence of which the initial temperature t_1 would rise), the final temperature t_2 would fall, or at least not rise proportionately with t_1. It is frequently stated by authorities on boiler testing that if the same number of heat units be liberated in a furnace per second in two cases—first, with a small air excess, and second, with a large air excess—the final or flue temperature in the first case will be the lower. This assumption may be true with some boilers, or with most boilers, or even with those of this plant, but after careful investigation of large numbers of actual simultaneous readings, the staff has become convinced that such a theory is both practically and theoretically untrue; and that, on the contrary, a rise of furnace temperature usually causes a proportionate rise of flue temperature, the ratio between these temperatures being almost independent of the mass of gases passing. For a long time this conclusion was hard to believe, for on closing the stack damper a little, at times, the combustion-chamber temperature rose and the stack temperature fell; yet nothing appears more certain on observation than that the sun moves around the earth.

It seemed almost axiomatic that the higher the initial temperature the greater the amount of heat which would pass into the boiler because of the greater temperature difference between gases and water, yet this proposition is only slightly true. Likewise it seemed axiomatic that a high combustion temperature would certainly aid combustion of smoke and hydrocarbons, which it would do if other accompanying conditions were not usually adverse enough to neutralize all gain. Because of these two propositions, which were apparently axiomatic, it was concluded that when the optical-pyrometer temperatures and the over-all efficiencies of the fuel bed, furnace, and boiler (72*) failed to agree, the pyrometer was given unreliable indications, through no fault of its own. So the first calculation was incidentally made of what was then called true boiler efficiency, in order to figure backward to the combustion-chamber temperatures, by means of the above formula, $\frac{t_1 - t_2}{t_1}$. The so-called true boiler efficiency was calculated for each of about 125 tests by means of the formula.

$$\text{True boiler efficiency} = \frac{\text{Efficiency } 72^*}{100 - [\text{CO loss in p. ct.} + (\text{unaccounted-for item in p. ct.} - 3 \text{ p. ct.})]}\cdot$$

All the above percentages were taken from the tests as calculated by the A. S. M. E. code. It will be noticed that the incomplete-combustion loss was taken as being the unaccounted-for item minus 3 per cent radiation. This was very crude, but the best we knew. The results were disappointing and not clear, but as negative results they were very instructive. Eighty-eight per cent of the so-called true boiler efficiencies fell between 70 and 75 per cent, and such uniformity surprised everyone. The combustion-chamber temperatures, calculated backward by equating these efficiencies to the expression $\frac{t_1 - t_2}{t_1}$ in which t_2 was known, turned out ridiculously low and the individual temperatures were very erratic. On leaving out a few abnormal tests, more than 90 per cent of those remaining had a so-called "true boiler efficiency" between 70 and 75 per cent. These calculations took much hard work, the details of which are omitted, inasmuch as it gave only negative and prophetic results that were of little value in themselves.

The great value of the work lay in the result that it shook previously conceived ideas, some of which were widely believed. The consequent inquiry took two forms—(*a*) a general mathematical study of the impartation of heat from fluids (including gases) to solids and vice versa,[a] and (*b*) a routine analysis of samples of gases from the rear of the combustion chamber and the stack for minute traces of hydrogen and hydrocarbons.

An ordinary Hemple pipette and absorption bulbs for analysis of illuminating gas are accurate only to about 0.2 or 0.3 per cent when very carefully manipulated. Unfortunately a mere trace of methane—for instance, to the extent of 0.1 per cent by volume in the flue gases—is sufficient to represent ordinarily a loss of 2 per cent of the coal due to incomplete combustion. (See p. 100.) Nevertheless, for some weeks several analyses were made daily for traces of hydrogen and hydrocarbons, and on several days these constituents occurred persistently and very appreciably, so as to indicate losses of many per cent due to incomplete combustion. On account of the well-known difficulty of obtaining accuracy in determinations of this kind, due to the small volumes of these gases that are ordinarily present, this work will not be published. It has, however, along with many kinds of circumstantial evidence, strengthened the belief that the losses due to incomplete combustion generally amount to several per cent of the potential heat in the coal burned. This presumptive loss will also be investigated in one or two other ways.

Incidentally it may be remarked that, if developed, such methods of measuring minute traces of hydrogen and hydrocarbons will be useful when applied to gas-engine exhaust gases. The mere analysis of exhaust gases for CO_2, O_2, and CO, resulting in no trace of CO, does not prove complete combustion by any means.

---

[a] It was fortunately found that John Perry had done much excellent, but mathematically involved, work on this subject; an account of it is given in his book "Steam Engines and Gas and Oil Engines."

THEORETICAL CONSIDERATIONS.

The tentative formulas developed by Perry are so significant and so important that a general outline of them is here given. According to his theory the rate of heat impartation to a boiler tube is, for ordinary gases, proportional to (1) temperature differences of the gases and the metallic surface; (2) density of the gas; (3) velocity of the gas parallel to the metallic surface, and (4) specific heat of the gases at constant pressure. The first of these factors is the only one usually thought of, and its applicability is perhaps self-evident.

In considering factor 2 it is plain that the individual molecules of gas give up their heat by vibrating against the metal. The greater the number of molecular impacts per second against a unit area of the tube the greater the amount of vibration (heat) imparted to the molecules of the metal. But the number of impacts is directly proportional to the density, or weight per liter or cubic foot. At a constant pressure (a little less than atmospheric in boiler practice), the density is inversely proportional to the absolute temperature, and at high-furnace temperature it is almost inversely proportional even to the temperature reckoned above steam temperature. On this account there is a direct neutralization of gain when striving for high temperature in steam-boiler practice, for as the temperature is raised the number of molecules in action against any portion of the heating surface is reduced.

In considering factor 3 a mental image should be formed of the appearance of a cross section of intensely magnified heating surface. The molecules of the metal would probably appear to be in an extremely rapid state of vibration, with spaces between them much larger than the molecules. Entangled among the outer molecules there would be comparatively stationary molecules of gas held close together in a dense film next to the metal. Farther out normal gas is reached, where the molecules are widely scattered. All these gaseous molecules, from those entangled among the surface molecules of metal to those in the gas of normal density, would be in an invisibly rapid state of vibration, but those close to the metal would be more or less "bound" by the attraction of the metal. Now, this layer of condensed gas, so to speak, is very adherent to the metal, and consequently a very poor conductor of heat (since heat in material bodies is a matter of the vibration of their molecules), so that the hope of getting heat through it lies in the possibility of dislodging slowly vibrating (cold) molecules from this layer and replacing them with rapidly vibrating (hot) ones. It can be imagined that as a stream of hot gas moves along the metal parallel to its surface, an average of one-third of its molecules are flying back and forth perpendicular to the surface, and the dislodging, sweeping, or scrubbing effect of these molecules on the layer of gas molecules adhering to the metal is proportional to the velocity of the mass of gas parallel to the heating surface. Thus it is that the velocity of gases through a boiler tube (a fire tube, for instance) is an important factor in heat absorption. It is this dislodgment that makes a boiler respond in amount of steam made to any reasonable demands put on it. If twice the mass of gas is put through the tube per second at the same initial temperature, very nearly twice as much steam will be generated on the other side of the tube.

In considering factor 4, the specific heat of the gas at constant pressure, it is evident that inasmuch as a cubic centimeter of any gas at any temperature and pressure contains the same number of molecules as a cubic centimeter of any other gas under the same conditions (Avogadro's law), and inasmuch as various gases on cooling give up various amounts of heat per degree of temperature drop—that is, they have different specific heats at constant pressure—a given number of molecular impacts of different gases will give up more or less energy, according as the specific heats of the gases are respectively more or less.

The relation between the heat transmitted per second per unit of heating surface and the four factors is expressed by the equation—

$$H = Cpv\ (T_1 - T_s)$$

where H = the amount of heat transmitted;
C = the specific heat times a constant;
p = density of the gas;
v = velocity of the gas parallel to the metallic surface;
$(T_1 - T_s)$ = the difference of temperatures of the gases and the water.

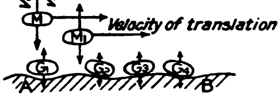


FIG. 57.—Diagram illustrating the theory of the dislodgment of adhering gaseous molecules from the surface of a metal plate.

Perry[a] arrives at the above equation by the following reasoning: Referring to fig. 57, let AB represent a small portion of a heating surface. G_1 to G_4 are molecules of the gas that are entangled among the molecules of the metal and therefore have no velocity parallel to the surface of the boiler plate; however, these molecules have velocity of vibration in all planes due to their temperatures. M and M_1 are molecules of the gas which have not only the velocity of vibration, but also the velocity parallel to the heating surface. Inasmuch as the conductivity of the metal itself in a boiler flue is so great that there is very little difference of temperature between the gas surface and water surface, the heat transmitted through the metal may taken to be equal to the heat imparted to the film of the s adhering to the metal. This assumption makes the temperure of the film equal to the temperature of the metal and also to at of the water. Now, suppose n represents the number of the lecules (M) which enter the adhering film of the gas, and also the mber of molecules (G) which leave the film of the elementary surce AB per unit of gas. Let T_1 be the average temperature of the tering molecules, and T_s the temperature of the film and of the ving molecules. The molecules enter and leave the film with an erage momentum in the axial direction that is proportional to the ial velocity (v) of the gases through the flue. The force of friction) is the axially directed momentum given to the adhering layer of lecules, so that per unit area the friction (F) is proportional to (as the momentum of a body is the product of its weight and its locity). The heat (H) given to the film per second per unit surce AB is proportional to n $(T_1 - T_s)$, or—

---

[a] Steam Engines and Gas and Oil Engines, pp. 587–591.

(1) $H = Cn\,(T_1 - T_s)$, where C is a constant.

(2) But as $F = Cnv$,

(3) Then $H = K\,\frac{F\,(T_1 - T_s)}{v}$, where K is another constant.

Now, the friction of fluids against a solid varies directly as the nsity and the square of the velocity of the fluid, or—

(4) $F = Cpv^2$, where p is the density of the fluid.

By substituting for F in equation 3 its value in equation 4, the ndamental equation as given before is obtained:

(5) $H = Cpv\,(T_1 - T_s)$.

In the foregoing equations the C and K are constants employed o that the sign of equality could be used.

Equation 5 gives the amount of heat transmitted per second per lementary area of heating surface. If the amounts of heat transnitted by every elementary area are added, the heat transmitted by he entire heating surface per second can be obtained. This can be lone by the use of calculus, as follows:

Take $T_1 - T_s = \Theta$; T_1 being the absolute temperature of the gases t the distance x from the furnace end of a flue of a total length l nd diameter D, and T_s being the temperature of the steam. Let V pounds of gases flow through the flue per second and let the pecific heat be a constant:

$$p = \frac{C}{v}, \text{ and } v = C'T$$

here C and C′ are temporary constants.

(6) Then $p = \frac{C''}{T}$, where C″ is a consolidation of C and C′ just above.

Also volume per second $= \frac{W}{p} = \frac{\pi D^2 v}{4}$, where D is the diameter of e fire tube and $\pi = 3.1416$.

(7) Whence $v = \frac{KW}{pD^2} = \frac{K'WT}{D^2}$, where K and K′ are constants.

Equations 6 and 7 are derived also from the laws that (1) the density of the gases varies inversely as the absolute temperature and (2) the velocity varies directly as the weight of the gas that passes through the flue in a second and as the absolute temperature, and inversely as the square of the diameter of the flue. By substituting the values of p and v from equations 6 and 7, equation 5 becomes—

$$H = \frac{Cv\Theta}{T} = -\frac{C'W\Theta}{D^2}.$$

Hence in a short length (dx) of the boiler flue the heat transmitted to the boiler is—

$$-C_pWd\Theta = \frac{C'W\Theta}{D^2} \times D\pi dx = \frac{CW\Theta dx}{D}$$

But $\int \frac{d\Theta}{\Theta} = -\int \frac{Cdx}{D}$. Integrating, $\log_e\Theta = -\frac{Cx}{D} + K$.

When $x = O$, $K = \log_e\Theta_o$. When $x = l$, $\log_e\Theta_l = -\frac{Cl}{D} + \log_e\Theta_o$ and

$\frac{\Theta_l}{\Theta_0} = e^{-\frac{Cl}{D}}$.

(8) $\therefore \Theta_l = \Theta_0 e^{-\frac{Cl}{D}}$.

The heat absorbed by the whole flue of the boiler per second is—

(9) $H = C_pW\left(\Theta_o - \Theta_e e^{-\frac{Cl}{D}}\right) = C_pW\Theta_0\left(1 - e^{-\frac{Cl}{D}}\right)$;

and the true efficiency of the flue is—

(10) $E = \frac{C_pW\Theta_0\left(1 - e^{-\frac{Cl}{D}}\right)}{C_pW\Theta_o} = 1 - e^{-\frac{Cl}{D}}$.

TRUE BOILER EFFICIENCIES DEPENDENT ONLY ON PHYSICAL SIZE, SHAPE, AND ARRANGEMENT OF BOILER.

Equation 10 states that the true efficiency of the boiler flue depends only on its length and diameter and not on the initial temperature of the gases. What is true about one flue holds good for all together.

The efficiency expressed by equation 10 is the true boiler-flue efficiency—that is, it is the ratio of the heat absorbed by the boiler flue to the heat available for absorption.

It must be remembered that in this discussion only the heat that is imparted to the boiler flue by convection and conduction has been considered. In reality the boilers receive heat also by radiation directly from the fire and from the hot walls of the furnace. According to the law of Stefan and Boltzmann the amount of energy radiated by a black-body surface to another body is proportional to the difference of the fourth powers of their absolute temperatures. The boile furnace radiating heat to the boiler is nearly a black-body surface, s at the heat received by the boiler by radiation may be expressed y the equation—

$$H=C\ (T_1^4-T_s^4)$$

here T_1 is the absolute temperature of the furnace, T_s the absolute mperature of the boiler tubes, and C a constant.

INFLUENCE OF VELOCITY OF GASES ON HEAT ABSORPTION.

The influence of the velocity of gases on the heat absorption may ppear at first somewhat improbable. However, inasmuch as high apacities of all types of boilers are obtained simply by burning more oal, which means making more hot gases and passing them over the eating surface at a higher velocity, it must be admitted that such an nfluence exists. Thus, for example, in locomotive practice the capacity is increased two or three times by doubling or tripling the rate of ombustion and therefore doubling or tripling the velocity through the boiler flues. Of course the rate of heat absorption by the fire box is affected principally by the initial temperature.

In fig. 6 (p. 15) the following three factors in heat absorption are hown, with their product, for the gas mixtures resulting when 1 ound of carbon is burned with various amounts of excess air: (1) emperature difference, (2) density of gases; (3) volume of gases, hich is proportional to velocity parallel to the heating surfaces.

The specific heats of products of combustion with the various air xcesses are nearly constant at 0.24, and therefore any errors introuced by neglecting to consider such varying compositions would be ss than about 1 per cent. In the case of some wet lignites the error ight be more, because of the presence of considerable percentages of ater vapor with a specific heat of 0.48 or higher. The temperatures f combustion were calculated on the assumptions that complete comustion is possible, and that the specific heats of oxygen, nitrogen, and arbon dioxide remain constant, which is not likely. Any error thus troduced into the calculated temperature is neutralized by an oppote and very nearly proportionate secondary error, introduced into the lculated density as a consequence of the primary error. On account these compensating errors the uppermost "products" curve is as liable as the whole theory.

The assumption was made that 1 pound of carbon was always rned in the same length of time, with various air excesses, and the sulting temperatures were calculated in degrees Fahrenheit. On e same data the relative densities of the resulting gaseous mixtures ere calculated, each at its respective temperature, taking as unit nsity that of the gases at 320° F. (the temperature of the boiler ater in this plant).

The lower curve, relative volume of products of combustion with creasing air supply, indicates that with large air excesses—that is, with low furnace temperatures—the actual volumes are comparatively high, but within the reasonable working range of even poor and good firing the volume of the products is nearly constant; as the air excess is reduced the temperature rises almost as fast and the effect on the resulting total volume is to decrease it very slightly.

Relative volume was used because the velocity of passage of the gases through the boiler is directly proportional to it, other things being equal, and, as already stated, velocity is one of the three most important factors determining the amount of heat imparted to the metal of the boiler tube.

It is assumed that in each case the products of combustion, generated always in the same length of time, are passed through a boiler fire tube. The upper ("products") curve gives by its ordinate the amount of heat absorbed by the first small portion of the tube during that length of time. On page 110 it is shown that this curve represents not only the amount of heat absorbed by the first short length of a tube but by the whole tube, so that this curve can be applied to the whole heat absorption of a boiler so far as absorption by convection is concerned; but it can not be applied to heat absorption due to radiation from fuel bed or hot brickwork.

The upper and final curve was obtained by multiplying together, for each of several temperatures along the whole range, the three factors (1) relative density of gases, (2) temperature of gases minus temperature of steam (T_1-T_s), (3) relative volume. The curve starts at zero heat absorption, because, although the density and volume are high, the temperature difference at 320° F. is zero, consequently the product of the three is zero. The ordinate figures at the left have no specific names, but merely furnish a scale on which to indicate relative magnitudes of volume, density, and products of these two, and temperature excess above that of boiler water. As applied to the upper curve these ordinates on the vertical scale do not mean B. t. u., though they are proportional to actual numbers of B. t. u. absorbed in any specific case.

On inspecting the upper curve the striking fact is its rapid approach to the horizontal, beginning at comparatively low furnace temperatures. For instance, at a furnace temperature of 2,000° F. (1,100° C.)—ordinary temperature scale; see second temperature scale at foot of chart—a temperature very easy to attain even with poor coals, the ordinate at the left is 9.0. At a furnace temperature of 3,000° F. (1,650° C.)—second temperature scale at bottom of chart—a temperature rather hard to attain and destructive to good fire bricks, the ordinate at the left is 9.5, only 5.5 per cent more than 9.0. Thus for all the extra trouble and expense of attaining the higher furnace temperature there is a gain in the efficiency of the boiler as a heat absorber of only 5.5 per cent, reckoning the efficiency calculation above atmospheric temperature. This gain is often largely neutralized by less complete combustion. The fact that the efficiency 72* is not improved by high combustion-chamber temperature is well illustrated in fig. 12 (p. 21), which is compiled from actual tests on coals of the same class from Illinois and Indiana.

It must be understood that this whole chart refers only to that part of a boiler which absorbs heat by contact with the hot gases. In a locomotive boiler this includes the tubes and to some extent the fire box. For a water-tube boiler of the Heine type, with the lower row of tubes inclosed in clay tiles, the chart includes all of the boiler except the lower row of tubes, which are exposed in the rear to radiation and are analogous to the fire box of a locomotive.

The following table gives a laborious method of calculating the relative amount of heat absorbed by the boiler when 1 pound of carbon is burned with various amounts of excess air. The table was calculated by first figuring the relative volume, the relative density, and the temperature elevation of the gases; then by multiplying these three together the relative heat absorption was obtained for the corresponding excesses of air. The curves of fig. 6 (p. 15) were plotted from the values given in this table:

Arithmetical calculation of relative amounts of heat absorbed by a hypothetical boiler.

	1.	2.	3.	4.	5.	6.	7.	8.	9.
Excess of air......per cent..	0	25	50	75	100	150	200	300	1,595
1. Pounds of O_2 per pound of carbon..............	2.67	3.33	4.00	4.67	5.33	6.67	8.00	10.67	45.20
2. Pounds of air per pound of carbon (4 parts N, 1 part O)................	13.33	16.67	20.00	23.33	26.67	33.33	40.00	53.33	226.00
3. C_p of products of combustion................	0.2360	0.2370	0.2373	0.2375	0.2376	0.2378	0.2380	0.2385	0.2390
4. Temperature rise due to combustion= $\frac{14{,}600}{C_p(\text{pounds of air}+1)}$..°F..	4,325	3,486	2,930	2,526	2,220	1,788	1,496	1,127	270
5. Temperature rise + 50 (which is atmospheric temperature)..... °F..	4,375	3,536	2,980	2,576	2,270	1,738	1,546	1,177	320
6. Absolute temperature of combustion....... °F..	4,836	3,997	3,441	3,037	2,731	2,299	2,007	1,638	781
7. Relative volume of unit mass of gases at temperature of line 6 when volume at 461° F. absolute=1...............	10.49	8.67	7.47	6.59	5.92	4.98	4.35	3.55	1.69
8. Relative total volumes of products of combustion, each at its final temperature of combustion=line 7×line 2..	1,139.8	144.5	149.4	153.5	157.88	165.9	174.0	189.3	382.0
Elevation of temperature of combustion above steam temperature:									
9. At 320° F., 75 pounds on gage ......°F..	4,055	3,216	2,660	2,256	1,950	1,518	1,226	857	0
10. At 390° F., 205 pounds on gage ....°F..	3,985	3,146	2,590	2,186	1,880	1,448	1,156	787	0
11. Density of products of combustion, each at its final temperature of combustion when density at 320° F.=1......	0.1615	0.1956	0.2269	0.2568	0.2856	0.3397	0.3891	0.4768	1.000
12. Line 11×line 9×line 8= H[a]....................	916	909	902	889	879	855	830	774	0

[a] This H is merely a number proportional to the heat absorbed.

The relative amount of heat absorbed by a boiler when various percentages of excess of air are used for combustion can be easily obtained by the following formula:

$$(11)\quad H = CW\left(\frac{60{,}900 - KW}{W-1}\right)$$

which is obtained as follows:

Let C = a constant, having a fixed value for each case.

p = the density of the gases, relative to any standard.

V = velocity past any small portion of heating surface under consideration, in any units.

T = absolute temperature of gases at any point under consideration, on any thermometric scale.

t = absolute temperature of boiler water on the same scale as T.

W = weight of gases resulting from combustion of 1 pound of carbon, expressed in any units of any system.

W − 1 = weight of air used per pound of carbon.

K = − Ta (temperature of atmosphere) + t.

According to our fundamental assumption (equation 5, p. 111), the heat transmitted per second per unit of heating surface is—

$$(5)\quad H = CpV\ (T-t).$$

But $p = \frac{C'}{T}\left(\frac{W}{W-1}\right)$, where C' is a new temporary constant. Also $V = C''\ TW$, where C'' is a new temporary constant.

The last two equations are derived from the fundamental properties of gases; the first one states that when 1 pound of carbon is burned with air the density of the resulting gases approaches that of air as the amount of air increases, which increase reduces the influence of the amount of CO_2 present; and the second, that the density decreases directly as the absolute temperature (T) of the resulting mixture increases. C′ is some constant, whose value will not be determined because all these results are relative only. This statement applies to all the C's used. Substituting the values of p and V in equation 5, we have—

$$H = C\left(\frac{W}{W-1}\right)\times\frac{C'}{T}\times C''\ TW\ (T-t) = \frac{CW^2}{W-1}(T-t)$$

on arbitrarily assuming that all constants, C, C′, and C″, are consolidated into a new C, as the result sought is to be relative only.

$$T - Ta = \frac{14{,}600}{0.24\ W} = \frac{60{,}900}{W}$$

hence

$$T = \frac{60{,}900}{W} + Ta$$

in which 14,600 = B. t. u. value of 1 pound of carbon and 0.24 =

pecific heat (approximately) of 1 pound of the gases of combusion at constant pressure. Substituting again, we have—

$$H=\frac{CW}{W-1}\left(\frac{60{,}900}{W}+Ta-t\right)W=CW\left(\frac{60{,}900-KW}{W-1}\right)$$

which is the equation given first above.

It was suspected that these calculations of heat imparted to the boiler surface might be slightly vitiated by the fact that CO_2, O_2, and N_2 have different specific heats. A trial calculation with two very different air supplies showed that this error could not be more than 1 per cent in favor of greater heat absorption with a low air supply.

The curves of fig. 20 (p. 29) were plotted from data obtained by formulas developed in the preceding paragraphs. This chart shows the same facts as fig. 6 (p. 15), but they are differently represented. The two charts were calculated at different times by different men, who used slightly different constants in some ways. One of them took account of the slight variation of composite specific heats of the gases with different air excesses and the other did not. Nevertheless, the two charts show graphically the same conclusion—that at low air excesses and high initial temperatures the heat absorption by the boiler increases only a few per cent as compared with moderate furnace temperatures. If we use the same temperature range as in the discussion of the curves of fig. 6 (p. 15)—2,000° F. (1,100° C.) to 3,000° F. (1,650° C.)—the amount of heat absorbed increases 7 per cent, as figured from the ordinate at the left. The increase calculated from the chart was 5.5 per cent.

The arrows attached to each curve indicate the coordinates to be used with it. The ordinate on the left, "Heat transmitted per second per unit of heating surface times a constant," is relative only, as indicated by the phrase "times a constant." This constant varies with the boilers. Every boiler has an individual constant, and according to this theory it is unchangeable except by changes in baffling, when it becomes another boiler with a new individual constant.

The curve labeled "Combustion temperature as affected by air supply" was calculated as explained for the chart shown in fig. 6 using constant specific heats.

The curve labeled "Heat absorption as affected by combustion temperature" is precisely the same curve as the upper curve of fig. 6, with the exception of the calculation as explained above.

The curve labeled "Heat absorption as affected by air supply" shows the same fact as the upper curve with reference to air supply per pound of carbon instead of the resulting temperature of combustion.

With 14 pounds of air per pound of carbon the ordinate at the left is 6.2. With 28 pounds of air the ordinate is 5.55—a decrease of about 10.4 per cent. The latter amount of air is high in practice. To reduce the heat absorption to 50 per cent of what it would be if the carbon were completely burned with the theoretical amount of air (11.50 pounds) would require 108 pounds of air per pound of carbon—an enormous excess.

In all such calculations of heat absorption it is plain that the more nearly the temperature of the absorbing medium approaches that of the atmosphere—that is, the lower the steam pressure—the less the harm done by excessive amounts of air and the larger the percentage of total heat absorbed. This is an argument in favor of low steam pressures with high superheats, as suggested tentatively on pages 102–105.

PRACTICAL APPLICATION OF THEORY OF HEAT ABSORPTION TO A FIRE-TUBE BOILER.

As a practical illustration of the meaning of these theoretical principles, several calculations were made in the case of a fire-tube boiler assumed to consist of a single tube 0.1 foot in internal diameter and 10 feet long.

From the work of page 112 is taken the equation, which expresses the quantity of heat passing through any given portion of the tube.

$$(9)\quad H = CpW(\Theta_{x_1} - \Theta_{x_2}) = W\Theta_0\left(e^{-\frac{cx_1}{D}} - e^{-\frac{cx_2}{D}}\right) \times 0.24$$

in which H = heat absorbed in B. t. u.

Θ_0. = elevation of initial temperatures above boiler-water temperature.

Θ_{x_1} = elevation of temperature of gases above that of boiler water at a point x_1 feet from the entrance end of the tube.

Θ_{x_2} = elevation of temperature of gases above that of boiler water at a point x_2 feet from the entrance end of the tube (x_2 is farther along the tube than x_1).

W = pounds of gases per pound of carbon.

e = base of hyperbolic system of logarithms = 2.718.

D = internal diameter of tube in feet.

c = a constant for any particular tube.

0.24 = the approximate specific heat of gases of combustion at constant pressure. This factor might well have been omitted and its effect on the equation accomplished by giving the constant "c," in the exponents of e, another value.

The following calculations assume that the metal of the tube is always kept at the water temperature, which is not true, inasmuch as there must be a difference of temperature in order to make the heat flow from the metal into the water. It must be understood at the outset that these calculations are not given for the purpose of proving anything, but merely to illustrate the concrete consequences of the theory. Other methods will be used and applied to actual boiler tests to show how closely the formula fits actual performances.

An ordinary locomotive boiler evaporates about 11.65 pounds of water (equivalent evaporation from and at 212° F.) per square foot of heating surface per hour. Our hypothetical boiler consists of one fire tube 10.0 feet long and of 0.1 foot internal diameter. Its heating surface is 3.1416 square feet and every second $\frac{11.65 \times 966}{60 \times 60} = 3.15$ B. t. u. are transmitted through each square foot.

Take the pounds of air per pound of carbon as 23.33, or 75 per cent excess above the theoretical, giving 24.33 pounds of gases of combustion per pound of carbon. The theoretical temperature of combustion is 2,576° F., assuming atmospheric temperature to be 50° F. In our case this is 2,576° − 320° = 2,256° F. above boiler water temperature. This 2,256° F. is our θ_0.

These calculations are to be for one second of time. It is more consistent with practice to assume that 1 pound of carbon is not burned in one second for 3.1416 square feet of heating surface, but in about 3,230 seconds.

Introducing this 3,230 as a correction factor in the above equation, and substituting all the above-calculated quantities; we get the following equation to be solved for "c," the physical or "size and shape" constant of this particular boiler:

$$3.1416 = 0.24 \times \frac{24.33}{3,230} \times 2,256 \times 2.718^{-\frac{c \times 0.0}{0.1}} - 2.718^{-\frac{c \times 10.0}{0.1}}$$

whence, on solving by logarithms, $c = 0.0147$.

Now let us take this hypothetical boiler of one fire tube and feed it with the gases resulting from the combustion of 1 pound of carbon completely burned (which is both theoretically and practically impossible with air supplies only a little above the theoretical), with increasing percentages of air excess. The factors are all grouped under case 1 of the table below; under case 2 are given parallel data for burning 2 pounds of carbon in the same time (3,230 seconds), and under case 3 for burning 10 pounds. The factors are repeated in the second and third cases to impress the fact that within reasonable limits the efficiency of a boiler proper as a heat absorber is independent of the capacity.

Calculations of the heat absorbed by a hypothetical boiler.

	Excess of air (per cent).	Case 1 (1 pound of carbon burned).			Case 2 (2 pounds of carbon burned).			Case 3 (10 pounds of carbon burned).		
		W.	Θ_0.	H.	W.	Θ_0.	H.	W.	Θ_0.	H.
1	0	$\frac{14.33}{3,230}=0.00443\ldots$	4,055	3.3218	$\frac{(14.33)2}{3,230}=0.00886$	4,055	6.6436	$\frac{(14.33)10}{3,230}=0.0443$	4,055	33.218
2	25	$\frac{17.67}{3,230}=.00547\ldots$	3,216	3.2530	$\frac{(17.67)2}{3,230}=.01094$	3,216	6.5060	$\frac{(17.67)10}{3,230}=.0547$	3,216	32.530
3	50	$\frac{21.00}{3,230}=.00650\ldots$	2,660	3.1972	$\frac{(21.00)2}{3,230}=.01300$	2,660	6.3944	$\frac{(21.00)10}{3,230}=.0650$	2,660	31.972
4	75	$\frac{24.33}{3,230}=.00753\ldots$	2,256	3.1416	$\frac{(24.33)2}{3,230}=.01506$	2,256	6.2832	$\frac{(24.33)10}{3,230}=.0753$	2,256	31.416
5	100	$\frac{27.67}{3,230}=.00856\ldots$	1,950	3.0866	$\frac{(27.67)2}{3,230}=.01712$	1,950	6.1732	$\frac{(27.67)10}{3,230}=.0856$	1,950	30.866
6	150	$\frac{34.33}{3,230}=.01063\ldots$	1,518	2.9839	$\frac{(34.33)2}{3,230}=.02126$	1,518	5.9678	$\frac{(34.33)10}{3,230}=.1063$	1,518	29.839
7	200	$\frac{41.00}{3,230}=.01269\ldots$	1,226	2.8769	$\frac{(41.00)2}{3,230}=.02538$	1,226	5.7538	$\frac{(41.00)10}{3,230}=.1269$	1.226	28.769
8	300	$\frac{54.33}{3,230}=.01682\ldots$	857	2.6655	$\frac{(54.33)2}{3,230}=.03764$	857	5.3310	$\frac{(54.33)10}{3,230}=.1682$	857	26.655
9	1,596	$\frac{227}{3,230}=.07027\ldots$	0	0.0000	$\frac{(227)2}{3,230}=.14054$	0	0.0000	$\frac{(227)10}{3,230}=.7027$	0	00.000

If it be true that by raising the initial temperature of the gases entering a boiler by 1,000° F. the amount of heat put into the boiler for every pound of fuel is increased by only a few per cent, and if it also be true that the small amount of oxygen present in case of high temperatures tends to reduce the speed and consequently the completeness of combustion, how, then, does it happen that (as is undoubtedly a matter of common observation) a large air excess certainly lowers the over-all efficiency decidedly? The explanation probably is that when the air excess is large it is probably very large through the holes in the fire, and insufficient through the little hills and cakes of coal on the grate, especially if the latter are underlaid with clinker; the result is that along with a general large air excess there may be much incomplete combustion. It comes back to the old story that the fuel bed and combustion space are to blame. The remedy lies in a more even fuel bed and gas-mixing structures in the combustion chamber, rather than a low air excess or a thick fuel bed. With gas-mixing structures a stronger draft must be used if the capacity is to be kept up.

In confirmation of the above supposition, that the air excess may be insufficient through cakes of coal, reference may be had to page 59, where analyses are given of gases collected at the surface of the fuel bed through a water-jacketed sampling tube. Many samples contain large percentages of CO, hydrocarbons, and hydrogen, and no O_2.

WATER CIRCULATION AS AFFECTING HEAT ABSORPTION.

It is assumed that in every case the water circulates rapidly, with the utmost freedom, and with the utmost responsiveness to variations in the amount of heat absorbed, so as to keep the metal of the tube always at water temperature. In practice this would not be true, if for no other reason than because twice the rate of heat absorption would perhaps require twice the speed of circulation; but, whereas the forces impelling circulation may, perhaps, increase directly with the increase in steam production, the retarding forces of friction increase as the square of the speed of circulation. The latter suggestions, however, are as yet only suppositions.

In each of the several calculations in the preceding table the quantity $e^{-\frac{cx_1}{D}}$ reduces to 1.0 because $x_1 = 0$; also the quantity $e^{-\frac{cx_2}{D}}$ has the constant value of 0.2295 because c and D are always the same and x_2 is taken in the table always as 10.0 feet. Therefore, the quantity in the parenthesis reduces to $(1 - 0.2295) = (0.7705)$. This constant is fixed once for all by the builder of the boiler when he chooses the length and diameter of the tubes. Consequently the heat absorbed by the tubes is directly proportional to the product of W and Θ_0, which represent respectively the weight of gases flowing per second and their initial elevation in temperature above that of the boiler water. All the calculations made in the case of this hypothetical boiler are for the purpose of giving specific instances showing that the product of W and Θ is very nearly constant for all reasonable conditions of good firing.

It has been stated before that the heat absorbed by a boiler is proportional to the initial temperature elevation above that of boiler water, times initial density relative to any (fixed) standard, times velocity of translation over the heating surface. A moment's reflection will make it clear that the product of the last two factors is at all times proportional to the mass (or weight) of gases passing per unit of time.

CALCULATION OF HEAT ABSORPTION ALONG A FIRE TUBE.

As an illustration of the method of using formula 9, a numerical example applied to the hypothetical boiler having a single tube of 0.1 feet internal diameter and 10 feet long is given below.

Assume that 1 pound of carbon is burned in 3,230 seconds with 25 per cent of excess of air. This is the same condition as given by the second line in the preceding table, case 1:

$$W = 0.00547 \text{ pound.}$$
$$\Theta_0 = 3{,}216^\circ \text{ F.}$$

Substituting these values, and also the value of $(1 - e^{-\frac{cl}{D}})$ for this particular boiler as calculated above, in equation 9, $H = W\ \Theta_0\ (1 - e^{-\frac{cl}{D}}) \times 0.24$, the heat absorbed becomes—

$$H = 0.00547 \times 3{,}216 \times 0.7705 \times 0.24 = 3{,}253 \text{ B. t. u.}$$

Instead of using formula 9, which has been derived by calculus, the amount of heat absorbed by the single-tube boiler can be approximately obtained by applying in steps the fundamental principle expressed by equation 5, $H = Cvp\ (T - t)$. Let the length of the tube be divided into twenty parts, and the heat absorbed by each part calculated by the above equation. Before these calculations can be made the constant C must be determined. This can be done by substituting in equation 9 the value of 0.5 for l, the already calculated value 0.0147 for c; and also the values of W and Θ of case 2 in the table (p. 120) and solving for H. This will be the heat absorbed by the first half foot of the tube. Substituting this value for H in equation 5 and also the calculated values for velocity, density, and the excess of temperature of the gases from tables on pages 115 and 120, and solving, we determine the value of C:

$$(9)\quad H = 0.00547 \times 3{,}216\ (1 - e^{-\frac{0.0147 \times 0.5}{.1}}) \times 0.24 = 0.291$$

$$(5)\quad 0.291 = 3{,}216 \times 19.45 \times 0.1955 \times C,$$

and hence

$$C = 0.0000238.$$

This procedure of determining the value of C had to be employed in order to put the two methods of calculating the heat absorbed on the same basis, making them comparable.

As 0.291 B. t. u. was absorbed from the gases by the first half foot the temperature was reduced $\frac{0.291}{0.24 \times 0.00547} = 222°$ F.; the elevation of temperature above that of boiler water at the entrance to the next or second half foot of the tube $= (3{,}216° - 222°) = 2{,}994°$ F.

The absolute temperature corresponding to 3,216° above steam temperature $= 3{,}216 + 320 + 461 = 3{,}997°$ F. Likewise the absolute temperature corresponding to 2,994° F. above steam temperature $= 2{,}994° + 320° + 461° = 3{,}775°$ F. Therefore the new velocity of the gas at entrance on the second half foot of the tube is $\frac{3{,}775}{3{,}997} \times 19.45 =$ 18.38 feet per second, inasmuch as the velocities are directly proportional to the volumes. Likewise the new relative density is $\frac{3{,}997}{3{,}775} \times 0.1956 = 0.2070$. It will be noticed that the simultaneous changes in velocity and density neutralize each other, but both are carried through the calculations for the sake of the principle.

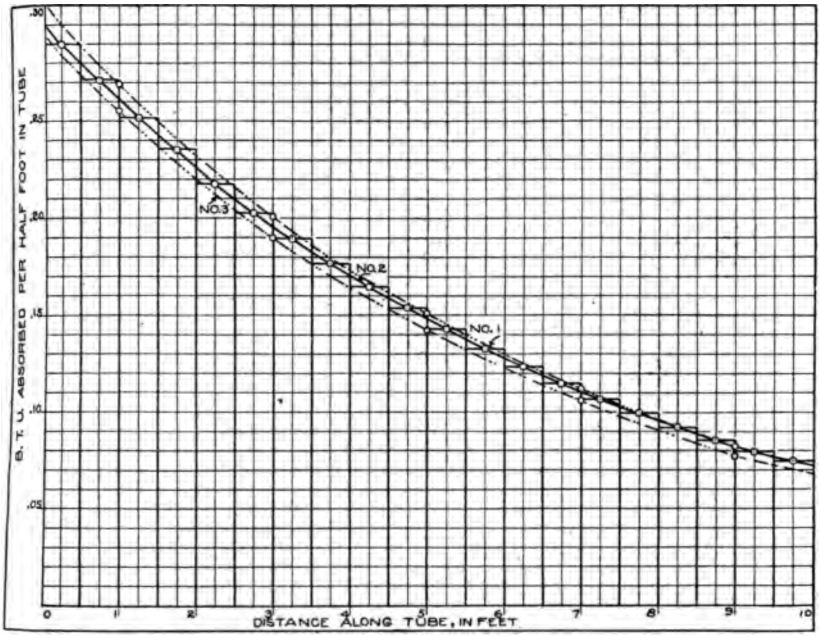
To go back to the fundamental principle, the amount of heat absorbed by the second half foot is equal to $2{,}994 \times 18.38 \times 0.2070 \times 0.0000238 = 0.272$ B. t. u.; and so on for each of the remaining eighteen half feet of the tube. On adding together all the partial H's the sum is 3.214 B. t. u., which is close to the value 3.253 obtained calculus. The step-by-step and calculus curves are both shown the chart (fig. 58). The areas under these curves do not represent ything; the vertical ordinates to the curves merely denote for each nall length the number of B. t. u. absorbed in that length.

On the same chart (fig. 58) is also given a curve obtained by calulus showing the amounts of heat absorbed per second when the ame quantity of carbon is burned with 100 per cent of air excess.

For the sake of clearness it is stated again that the step-by-step process was merely an approximate arithmetical method of integrating the formula—

H = B. t. u. absorbed for length under consideration =

$$W\ \Theta_0\times 0.24\left\{e^{-\frac{cx_1}{D}}-e^{-\frac{cx_2}{D}}\right\}$$



IG. 58.—Relative B. t. u. absorbed at different points in a boiler tube 10 feet long and 0.1 foot internal diameter: Curve No. 1, calculated by calculus, using 25 per cent of air excess; No. 2, calculated by steps, using 25 per cent of air excess; No. 3, calculated by calculus, using 100 per cent of air excess

The arithmetical method gives results about 1 per cent smaller in is individual case than the integration by calculus.

Inasmuch as an illustration has been given showing how closely vithin about 1 per cent) the arithmetically calculated absorption of eat agrees with the more correct value calculated by calculus when e carbon is burned with 25 per cent excess of air, the arithmetical lculation was not repeated for 100 per cent excess of air. The irves of heat absorption and of drop of temperature along the length the boiler tube, 0.1 foot internal diameter and 10.0 feet long, are given in figs. 58 and 59. It will be noticed that the total heat ab sorbed is 3.0866 B. t. u., which is only 5.2 per cent less than with th smaller air supply. This result is an illustration of the statemen that a boiler will absorb about the same percentage of the heat of pound of fuel completely burned, whatever the air supply per poun of fuel, if the variation is within reasonable limits.

The curves of temperatures along the tube, when using 25 an 100 per cent excess of air, shown on fig. 59 (p. 125), were obtain as follows: Those on the step-by-step curve were taken directly fro the column headed "Θ_0" in the following table:

Heat absorption along a hypothetical boiler tube, by sections, at 25 per cent of air exce

	Initial minus boiler-water temperature (°F.). Θ_0	Velocity of gas at entrance to each section (feet per second).[a] v	Density of gas at entrance to each section. Gas at 320°=1. p	Partial he absorbed (B. t. u.). $H=\Theta\times v\times$ $p\times C$.[b]
Half foot:				
First	3,216	19.45	0.1956	0.2
Second	2,994	18.38	.2070	.2
Third	2,787	17.38	.2189	.2
Fourth	2,595	16.45	.2312	.2
Fifth	2,416	15.59	.2440	.2
Sixth	2,250	14.80	.2571	.2
Seventh	2,095	14.06	.2709	.1
Eighth	1,951	13.36	.2850	.1
Ninth	1,861	12.70	.3000	.1
Tenth	1,691	12.12	.3149	.15
Eleventh	1,574	11.55	.3301	.14
Twelfth	1,465	11.02	.3460	.13
Thirteenth	1,364	10.54	.3620	.12
Fourteenth	1,270	10.09	.3780	.11
Fifteenth	1,183	9.65	.3950	.10
Sixteenth	1,102	9.26	.4110	.10
Seventeenth	1,026	8.89	.4290	.09
Eighteenth	955	8.54	.4460	.08
Nineteenth	890	8.26	.4590	.08
Twentieth	829	7.97	.4760	.07
For whole 10.0 feet				3.21
Final temperature above steam	772			

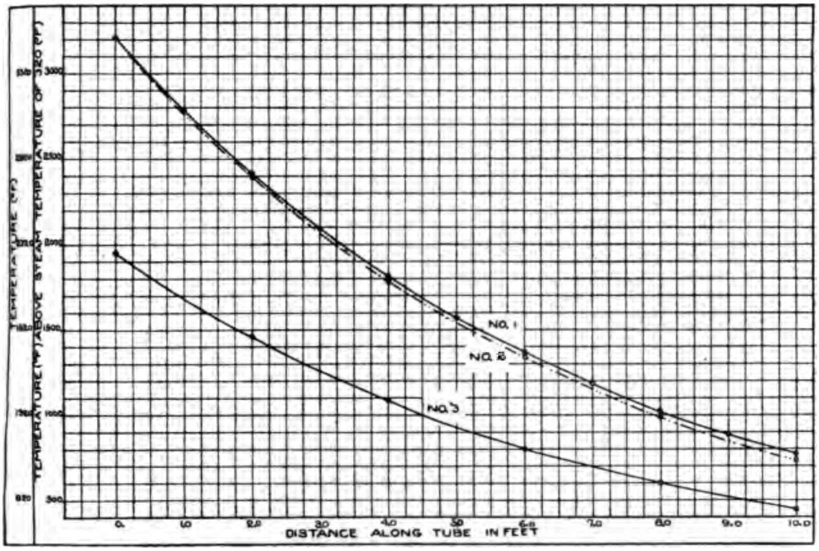
[a] Weight of gases per second in pounds$=\frac{17.67}{3230}=0.00547$.

[b] Constant=0.0000238.

The five points on the curves obtained by calculus were located b using formula 8 for five lengths of tube, 0 to 2 feet, 0 to 4 feet, 0 to feet, 0 to 8 feet, and 0 to 10 feet.

HIGHER INITIAL TEMPERATURE MEANS HIGHER FINAL TEMPERATURE WHE HEAT ABSORPTION IS BY CONVECTION ONLY.

Regarding the two curves of temperature changes along the lengt of the hypothetical boiler tube when using 25 per cent and 100 per cen excess of air, it appears that however long the tube might be, the upp temperature line would never meet the lower one, and would neve cross it. This statement is also borne out by a consideration of th mathematical equation on which the curves are based. It is in direc contradiction to a statement often made that the higher the initia *temperature the lower* the final, provided the amount of heat liberat r unit of time is the same in every case. For many months most the authors of this bulletin thoroughly believed this idea, and it as only when they took many cases and tried to plot the relations etween combustion-chamber and stack temperature that they saw he two rise and fall together. Later on the work of Perry on the oiler as a heat absorber was developed and it was realized that the acts, at the testing plant at least, agreed somewhat with the theory nd pointed in the right direction. In this connection it must be emembered that a lower flue temperature does not always indicate a lower B. t. u. loss, but generally a larger one, because the mass of gases is more than enough larger to make up the difference; but in any one boiler the net difference is usually within 5 to 15 per cent.



IG. 59.—Relative temperatures of the products of combustion passing through a boiler tube 10 feet long and 0.1 foot internal diameter: Curve No. 1, calculated by steps, using 25 per cent of air excess; No. 2, calculated by calculus, using 25 per cent of air excess; No. 3, calculated by calculus, using 100 per cent of air excess.

MODIFYING FACTORS OF THE THEORY OF HEAT TRANSMISSION.

In the section on the theory of heat transmission the assumption vas made that the gas comes directly into contact with the metal urface of the boiler flue, and also that the water in the boiler absorbs he heat as fast as the metal can transmit it. In a commercially perated boiler neither of these assumptions is true. The metal of the boiler flue is insulated from the gas with a layer of soot, and from the water with a layer of scale and, perhaps, a layer of steam. As these layers of soot, scale, and steam are very poor conductors, a resistance many times greater than that of the metal of the boiler tube itself is offered to the passage of heat. It is evident that under such conditions the difference of temperature between the first layer of gas and that of the first layer of water must be greater than it would have to be if the insulating layer of soot, scale, and steam were not present, in order that the heat should flow from the gas to the water at a certain desired rate. This temperature difference must be larger the greater the required rates of heat transmission and the thicker the insulating scales. Inasmuch as capacity is the rate of heat absorption, this explains why at higher capacities the gases leave the heating surface of a boiler at higher temperatures than they do at lower capacities. It is clear, then that in order to have the heating surface efficient it must be kept free from soot and scale, and the bubbles of steam must be removed from the surface as fast as they form, so that the water can come directly into contact with the metal. This last requirement emphasizes the importance of water circulation in the boiler. The faster the circulation of water the faster are the bubbles of steam carried away and the better is the contact between the metal and the water.

It is reasonable to expect that in the Heine boiler when the capacity is increased the rate of circulation of water should be increased in about the same proportion, in order that the metal surface may be kept free from steam bubbles. To what extent this is true is shown in the chart (fig. 7, p. 16) that gives the relation between the circulation of water in a water tube boiler and the capacity.

The effect of the above-named modifying factors—that is, the resistance offered to heat passage by soot, metal, scale, and steam—is to increase the temperature difference between the outside surface of the adhering gas film and the film of water coming into contact with the steam layer when the rate of heat transmission—that is, the capacity—increases. By taking into consideration these factors, and also the fact that the adhering film of gas does not consist of a layer 1 molecule thick, but has a sufficient thickness to offer an appreciable resistance to the passage of heat through it, a formula similar to that whose derivation is shown on pages 110 to 112 can be obtained that will agree very closely with the actual performances. Fig. 60 gives the temperature gradient of the moving gases and also the temperature gradients along the surfaces of contact of the different resistance-producing layers. Let dl be any elementary length of the heating surface; $T-t_1$ the temperature difference between the moving gases and the outside surface of the adhering film of the gas, and t_1-t the temperature difference between the latter and the water film coming into contact with the layer of steam. The temperature differences between the individual layers are expressed by $a-b$, $b-c$, etc., as shown in the figure. The heat transmission from the moving gases at the temperature T to the adhering immovable film at the temperature t_1 occurs by convection, according to the relation expressed by equation 1, $H=Cpv\ (T-t_1)$, and the heat transmission from the gas film through the layers of gas, soot, metal, scale, and steam into the water at temperature t occurs purely by conduction, and follows the law expressed by equation 12:

$$(\mathbf{12})\ H = \frac{k}{b}(t_1 - t)$$

where k is the average conductivity for heat of the materials comprising the layers and b their total thickness. As $\frac{k}{b}$ is a constant, H varies only with the value of $(t_1 - t)$.

If the rate of heat impartation by convection is higher than the rate of transmission by conduction, the heat will accumulate in the resisting layers on the gas side and t_1 will rise. The rise of t_1 will decrease the rate of heat impartation by convection and increase the rate of heat transmission by conduction. The opposite will occur if the rate by convection is lower than the rate by conduction. There is a constant equalization of the two rates, so that equations 1 and 12 can be written as follows:

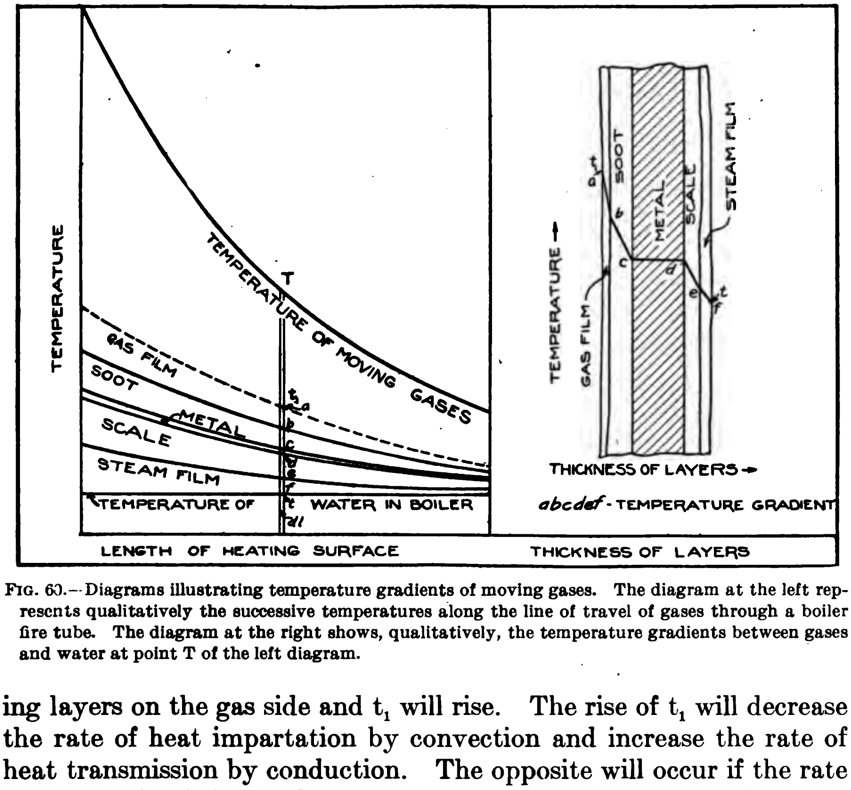


FIG. 60.—Diagrams illustrating temperature gradients of moving gases. The diagram at the left represents qualitatively the successive temperatures along the line of travel of gases through a boiler fire tube. The diagram at the right shows, qualitatively, the temperature gradients between gases and water at point T of the left diagram.

$$(\mathbf{13})\ Cpv\,(T - t_1) = \frac{k}{b}(t_1 - t).$$

The heat transmitted per second by any portion of the heating surface is then expressed by equation 1, $H = Cpv(T - t_1)$, in which T and t_1 are variables, T depending on the conditions of combustion and the rate of heat impartation, whereas t_1 depends on the rate of heat impartation only. From equation 12—

$$t_1 = H\frac{b}{k} + t.$$

Substituting this value for t_1 in equation 1, and simplifying, we get equation 14:

$$(14)\quad H = \frac{C\,p\,v\,(T - t)}{1 + \frac{b}{k}\,C\,p\,v}.$$

Let W be the weight of gases passing the heating surface per second, then as $p = \frac{C'}{T}$ and $v = C''\,W\,T$, $C\,p\,v = C_1\,W$, where C_1 is a new constant.

Let $C_1\frac{b}{k} = K$, and $(T - t) = \Theta$; on substituting these values in equation 14 it becomes—

$$(15)\quad H = \frac{C_1\,W\Theta}{1 + K\,W}$$

and the heat absorbed by any elementary length of heating surface per second is $-Wd\Theta = \frac{C_1\,W\Theta}{1 + K\,W}\,dl$, or—

$$(16)\quad -\frac{d\Theta}{\Theta} = \frac{C_1\,dl}{1 + KW}.$$

On integrating equation 16, there results—

$$\log_e\Theta = \frac{C_1 l}{1 + KW} + K.$$

When $l = O$, $\log_e\Theta_0 = K$. Hence

$$\log_e\Theta - \log_e\Theta_0 = -\frac{C_1 l}{1 + KW}, \text{ or}$$

$$\log_e\frac{\Theta}{\Theta_0} = -\frac{C_1 l}{1 + KW}$$

whence—

$$(17)\quad \Theta = \Theta_0\,e^{-\frac{C_1 l}{1+KW}}$$

The heat absorbed by the length of heating surface equal to l is—

$$(18)\quad H = 0.24W\Theta_0\,1 - e^{-\frac{C_1 l}{1+KW}}$$

and the true efficiency of the heating surface is—

$$(19)\quad E = 1 - e^{-\frac{C_1 l}{1+KW}}.$$

Equation 19 states that the true efficiency of the heating surface is independent of the initial temperature of the gases so far as heat absorption by convection is concerned and that it decreases when the weight of gases passing over the heating surface increases—that is, when the capacity increases. The constant K depends on the condiion as regards cleanliness of both sides of the heating surface. If here were no resistance to the passage of heat, K would be equal to 0, the denominator would reduce to 1, and equation 19 would be the same as equation 10, D being constant in any one boiler, fixed once for all by the maker.

It is probable that the film of gas which is entangled in the rough sooty surface is of considerable thickness and that rather a large part of the resistance to the passage of heat is perhaps due to this film. It is also very likely that as the velocity of the gases increases their scrubbing action reduces the thickness of this film. This probably again adds to the importance of the velocity of gases along the heating surface.

The influence of the velocity of gases on the thickness of the film has not been taken into consideration in the derivation of equation 8. It would somewhat lessen the effect of W on the true efficiency; hat is, it would make the true boiler efficiency more nearly constant or all rates of working.

The velocity of circulation of water in the boiler is equal in importance to the velocity of the gases on the outside of the heating surface. The same mathematical reasoning can be applied to the influence of velocity of gases on the impartation of heat. The amount of steam ormed increases directly with the rate of heat transmission, and if the scrubbing action of the circulation of water is insufficient to remove t from the heating surface the resistance due to the layer of steam formed will rise with the rate of making steam. Lack of adequate circulation of water in a boiler is a check to capacity. The fact is becoming well known that small automobile boilers are making steam ten to twenty (or even more) times as fast per unit of heating surface as stationary boilers in power plants, and at better efficiency. This increased rate of steaming is attained purely by high velocity of water and steam circulation over the heating surface.

Formulas 17, 18, and 19 apply only to heat imparted to the boiler by convection and conduction. The heat which is received by radiation perhaps follows nearly the radiation law of Stefan and Boltzmann, expressed by equation 20,

$$(20)\quad H = C\,(T^4 - t_1^4),$$

where T is the absolute temperature of the heat-radiating body, t_1 the absolute temperature of the heat-receiving body, and C a constant.

In the case of a boiler, t_1 is the temperature of the outside layer of soot on the heating surface, and is a variable, depending on the rate of heat transmission through the sooted and scaled boiler plate. The heat transmitted through the boiler plate is given by equation 12, $H = \frac{k}{b}(t_1 - t)$. As the heat transmitted through the boiler plate is equal to the heat received by the surface of the plate by radiation, equations 12 and 20 can be written as follows:

$$C\ (T^4 - t_1^4) = H = \frac{k}{b}\ (t_1 - t).$$

On substituting the value of t_1 from equation 12 in equation 20, the latter becomes—

(20) $H = C\left[T^4 - (H\ \frac{b}{k} + t)^4 \right].$

This is an equation of the fourth degree, and the value of H can be obtained by the method of approximation.

By the use of equations 18 and 20 it is possible to obtain the total heat absorbed by any boiler and its true efficiency. However, before the equations can be used the constants in them must be determined for any particular boiler. The four constants in the two equations were determined for the Heine boilers at the fuel-testing plant in this way: Four specific cases were selected from the results of boiler trials and from the resulting equations the values of the constants were approximated. The two equations applied to these Heine boilers are—

(18) $H_c = 0.24W\Theta_0\ (1 - e^{-\frac{2.7}{1+0.1524W}})$, and

(20) $H_r = \frac{1}{540 + 10^8}\left[T^4 - \left(\frac{H}{0.145} + t \right)^4 \right];$

where t at 80 pounds gage pressure is 785° F. absolute and Θ_0 is $T - t$, T being the actual absolute temperature in the furnace in degrees Fahrenheit; H_c the heat received per second by the boiler by convection and conduction; H_r the heat received per second by radiation from the brickwork, etc., of the combustion chamber; and W the weight of gases in pounds passing over the heating surface per second. Within the workable temperature range from 2,461° to 3,361° F. absolute, H_r is obtained with fair accuracy by the simple straight-line equation—

(**21**) $H_r = 0.144T - 294.$

The per cent of heat received by radiation referred to total heat available is—

(**22**) $E_r = \frac{(0.144T - 294) \times 100}{0.144T - 294 + 0.24W\Theta_0}$

and the per cent of heat received by convection referred to total heat available is—

(**23**) $E_c = 100\ (1 - e^{-\frac{2.7}{1+0.1524W}}) \times (1 - E_r).$

The true boiler efficiency is then expressed by equation 24:

(**24**) $E_4 = E_r + E_c.$

Heat which is radiated to the boiler during the combustion of fuel is not sensible heat, because it does not raise the temperature of the gases. *This is the* reason why the heat radiated is added to the heat in the gases at the temperature T to obtain the total heat available for the boiler. E_r has been calculated by formula 22 for five values of W and the results are plotted on the lower part of fig. 61. $\left(\frac{E_c}{1-E_r}\right)$ has been calculated by equation 23 and the results are plotted on the upper part of fig. 61. The true efficiency of these par-

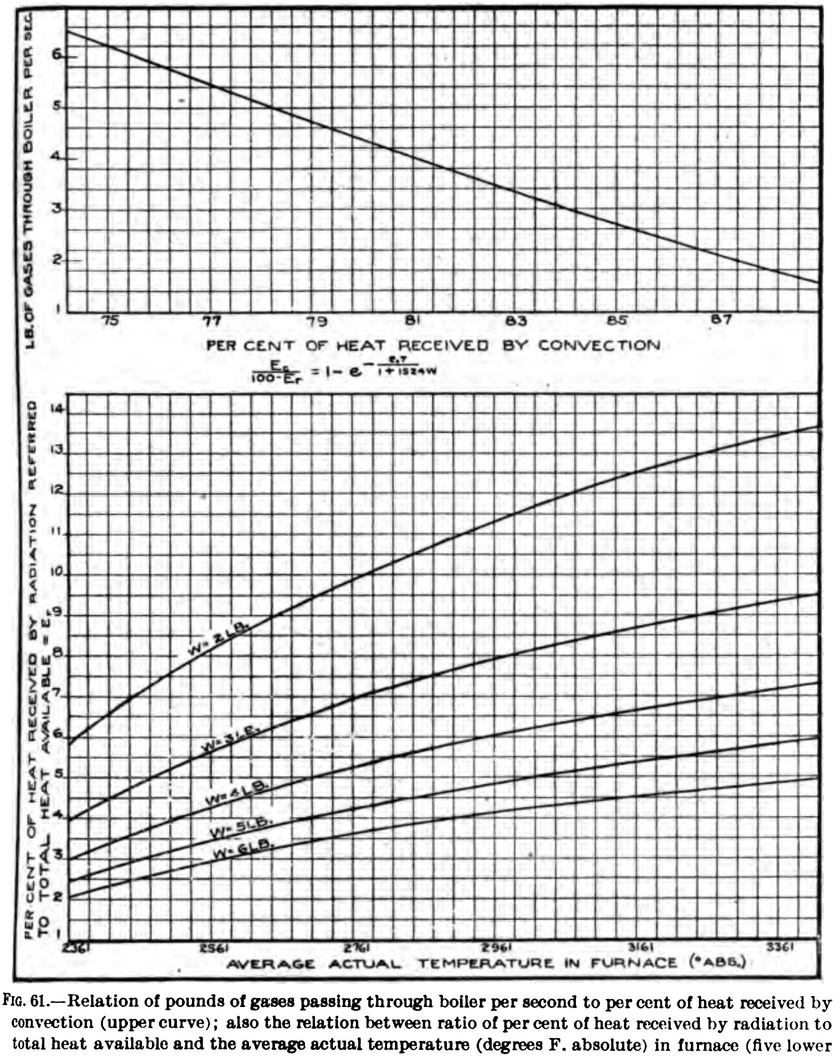


FIG. 61.—Relation of pounds of gases passing through boiler per second to per cent of heat received by convection (upper curve); also the relation between ratio of per cent of heat received by radiation to total heat available and the average actual temperature (degrees F. absolute) in furnace (five lower curves).

ticular Heine boilers can be obtained for any condition within the practice of operation by a simple multiplication and addition.

Example 1. Let 5 pounds of gases pass over the heating surface in a second, and let the actual furnace temperature be 2,961° F. absolute. In fig. 61 (lower part), where $W = 5$ pounds and $T = 2,961°$ F. absolute, $E_r = 4.85$. In the upper curve of fig. 61, where $W = 5$ pounds, $\frac{E_c}{100 - E_r} = 78.15$. Then $E_4 = E_r + E_c = 4.85 + 78.15 \times (100 - 4.85) = 79.15$.

Example 2. Let $W = 3$ and $T = 3,261°$ F. absolute. Then $E_r = 9$ and $\frac{E_c}{100 - E_r} = 84.2$. $E_4 = E_r + E_c = 9 + 84.2 \times (100 - 9) = 85.62$.

Example 3. Let $W = 5$ pounds and $T = 3,261°$ F. absolute. Then $E_r = 5.6$ and $\frac{E_c}{100 - E_r} = 78.15$. $E_4 = E_r + E_c = 5.6 + 78.15 \times (100 - 5.6) = 80.4$.

In examples 2 and 3 the capacities are to each other very nearly as 3 is to 5; that is, if the capacity is 90 per cent in example 2 it is nearly 150 per cent in example 3.

Equations 18 to 24 are rational formulas, and are interesting because they are derived purely by mathematical reasoning from the fundamental laws of physics—that is, the laws of convection, conduction, and radiation of heat. It is gratifying that the actual performance of two individual boilers throughout wide ranges of furnace temperature and rates of combustion has been very closely approximated by a formula based on fundamental principles of physics—the laws of the kinetic theory of gases and liquids and of the transfer of heat by conduction and radiation.

TEMPERATURE TEST OF PERRY'S EQUATION.

For the purpose of testing Perry's equation, that "The temperature above boiler water of the gases entering a boiler = the temperature above boiler water of gases leaving the boiler, times a constant," all tests on which approximate combustion-chamber temperatures were taken by a Wanner optical pyrometer were used—a total of 215 tests. For convenience, the temperature of the water in the boiler was assumed to have been always 317° F. This temperature varied 5° or 6° in different tests. The resulting constants, which ranged from 4 to 14, were collected in groups, showing that two fall between 4.5 and 5, six between 5 and 5.5, nineteen between 5.5 and 6, etc. These relations, plotted on the chart (fig. 62), show that the peak comes at 7.25; the arithmetical average of all the values is 7.43. It will be noticed on the curve that there are more high values than low values, whereas a true probability curve is symmetrical on both sides of the vertical axis.

On looking up the high values, especially those between 10 and 10.5, the average point of which is rather high, it is found that they belong to tests having flue temperatures that are suspiciously low for various *reasons*. But leaving in this point and casting out the six tests having the highest values of the constant (all of which have the suspiciously low flue temperatures), the remaining 209 tests average 7.3—about the same value as that of the peak of the curve.

This means that if the excess of combustion-chamber temperature above steam temperature be divided by 7.25 the quotient will be the probable excess of flue temperature above steam temperature. This result is now to be compared with the "true boiler efficiency," which was tentatively found to be 82.7 per cent. The calculation to be made assumes that the specific heat of the gas mixture is constant up to 2,500° F., which is probably not true. It is also assumed that no cold air leaks into the gas stream between the entrance to the boiler and the flue, which we know is far from true.

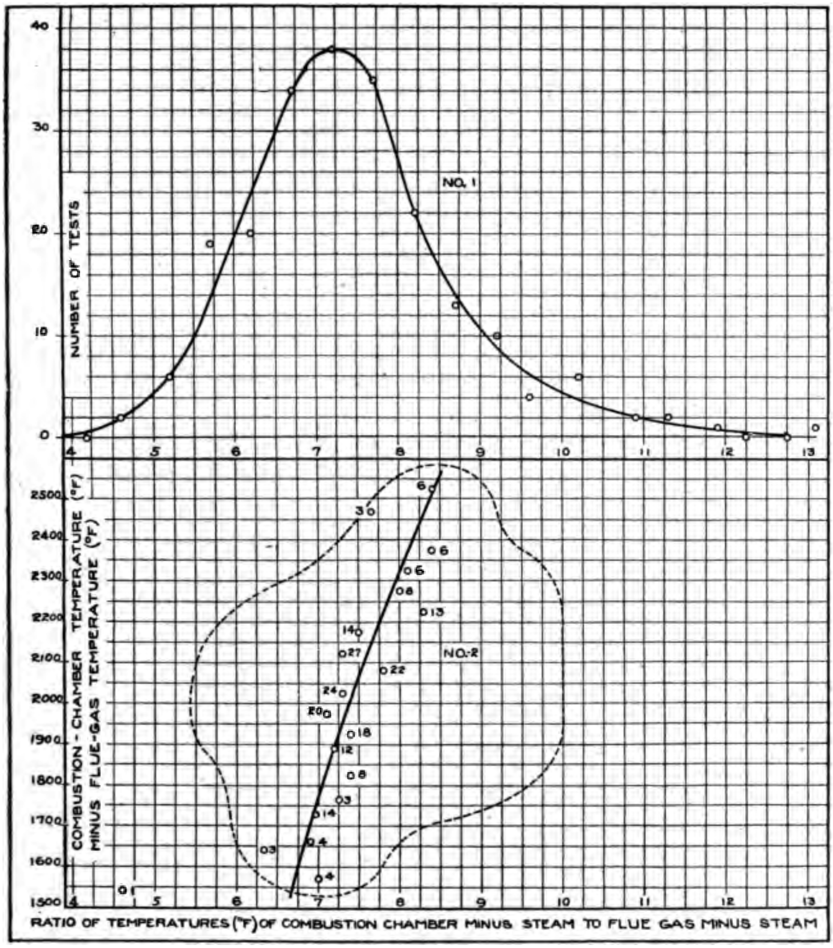


FIG. 62.—Classification on basis of ratio of temperatures of combustion chamber minus steam to flue gas minus steam: Curve No. 1, probability curve of ratio (maximum point, 7.25); No. 2, relation of ratio to combustion-chamber temperature (°F.).

On the assumption that the initial temperature of the gases is 2,500° F., this is 2,500° − 317° = 2,183° F. above steam temperature; 2,183° divided by 7.25 = 301° F. the probable excess of flue temperature over boiler-water temperature. Now, out of the maximum possible 2,183 B. t. u. that might be absorbed by a boiler from each 4.15 or $(\frac{1}{0.24})$ pound of furnace gases, this boiler absorbed 2,183 − 301 = 1,882 B. t. u., which is 86.2 per cent of 2,183. That is, the true boiler efficiency calculated from initial and final temperature of gases is 86.2 per cent, which is fairly close to the 82.7 per cent found above.

Into this method of calculating the "true boiler-efficiency constant" there enter two errors, which will be roughly corrected in a specific calculation. The combustion-chamber temperature, as read by the optical pyrometer, is known to have been usually low. In this calculation it will be assumed that the pyrometer read 100° low, making the true initial temperature 2,600° F.; also it will be assumed that the air which leaked through the setting amounted to 20 per cent in mass of the gases which entered the boiler, which is an approximately true average, and that all of this air entered the stream of gas after leaving the boiler and before reaching the flue thermometer, which is not true.

The initial temperature is 2,600° − 317° = 2,283° F above steam temperature. If we use the old constant, 7.25, the flue temperature should be 2,283° F. ÷ 7.25 = 315° F. above steam temperature, which would make the flue temperature 632° F., say 630°. Remembering that this 630° is the result of the cooling of the gases by the boiler and also of the addition of cold air at 60° F. to the extent of 20 per cent, we can calculate that the flue temperature would have been about 768° F. had this admixture not occurred. Subtracting 317° from 768°, we have left 451° F. Thus out of the maximum 2,283 B. t. u., which a boiler might possibly be built to absorb from every 4.16 pounds of gases, this boiler absorbs 2,283 − 451 = 1,832 B. t. u., which is 80.3 per cent of 2,283. That is, the true boiler efficiency thus approximated by initial and final temperature of furnace gases is 80.3 per cent; before correction it was 86.3 per cent. The mean is close to the value 82.7 found by the entirely different heat-balance method.

RATIO MODIFIED IN PRACTICE BY INITIAL TEMPERATURE.

The lower curve of fig. 62 (p. 133) was formed for all the individual tests from the same ratios as the upper curve. The ratios of excess of furnace temperature to excess of flue-gas temperature were all plotted preliminarily on a sheet of coordinate paper, and the average value of the ratios falling in each horizontal temperature strip 50° wide was determined. These average values are given by the positions of the small circles, the number beside each giving the number of tests falling in that horizontal temperature strip. It will be noticed that the heavy line, drawn through the points from these averages with regard to their respective weights, slopes upward to the right—that is, with the higher furnace temperatures the boilers absorb a slightly larger portion of the heat available to them, only that heat in the gases which is above steam temperature being considered as available. The dotted line marks the boundary of the field covered by the individual ratio points.

As a numerical example let us take two cases and figure backward from the ratios to the "true boiler efficiencies."

Case 1: From the curve (the lower one) we see that when the temperature of the combustion chamber minus steam temperature equals 1,700° F., the ratio averages 7.0. Dividing 1,700° by 7.0, we get 243°, the average excess of the flue temperature above steam temperature at this initial-temperature excess.

$$\frac{1{,}700-243}{1{,}700}=85.7 \text{ per cent} = \text{true boiler efficiency.}$$

Case 2: From the same curve take initial temperature excess = 2,400° F.; the ratio is 8.2; $2{,}400 \div 8.2 = 293°$, the average excess of flue temperature over steam temperature under these conditions.

$$\frac{2{,}400-293}{2{,}400}=87.7 \text{ per cent} = \text{true boiler efficiency.}$$

The value in the first case was 85.7 per cent. The second case then gives an increase of 2 per cent of the heat which could possibly be absorbed.

One tentative explanation of this slight increase of efficiency at higher temperatures is that the boiler absorbs heat not only by convection from the gases among its tubes, an action to which Perry's tentative theory is applicable, but also, more or less, by radiation from the bottom and sides of the combustion chamber onto the bare tubes in the rear, where the gases leave the combustion chamber. This radiation does not increase directly with the furnace temperature, but varies as the difference of the fourth powers of the absolute temperatures of the radiating and receiving bodies. That is, if T_F represents the absolute temperature of the furnace walls "visible" to the exposed tubes, and T_T the absolute temperature of the outer surface of the cold tubes, the heat absorbed by the tubes due to radiation is proportional to $(T_F^4 - T_T^4)$. It is easily seen that inasmuch as T_T is practically constant, changes in T_F will change the value of the parenthesis a great deal. Consequently, as the temperature of the combustion-chamber walls rises the amount of heat absorbed by the exposed portion of the lower row will increase much more rapidly; and though this heat is only a part of the total heat absorbed by the whole boiler, its rapid rate of increase may raise the "true boiler efficiency" a little.

The lower curve of fig. 62 (p. 133) bends to the right as it ascends. If the radiation increased directly as the temperature difference between the furnace walls and bare tubes, the line might well be straight; but as it increases according to the fourth-power law, the curve should bend to the right.

Thus by two entirely different and independent methods we have arrived at the conclusion that the true efficiency of these boilers is nearly constant. These methods are the heat-balance method described on pages 139–141, and the excess-temperature-ratio method just given. On pages 143–145 another independent method arriving at the same conclusion is given, with the additional refinement that true boiler efficiency increases slightly not only with increase of furnace temperature, but also with decrease in the amount of steam made. It must be distinctly understood that all these ideas are advanced tentatively only, as another attempt to separate furnace and boiler.

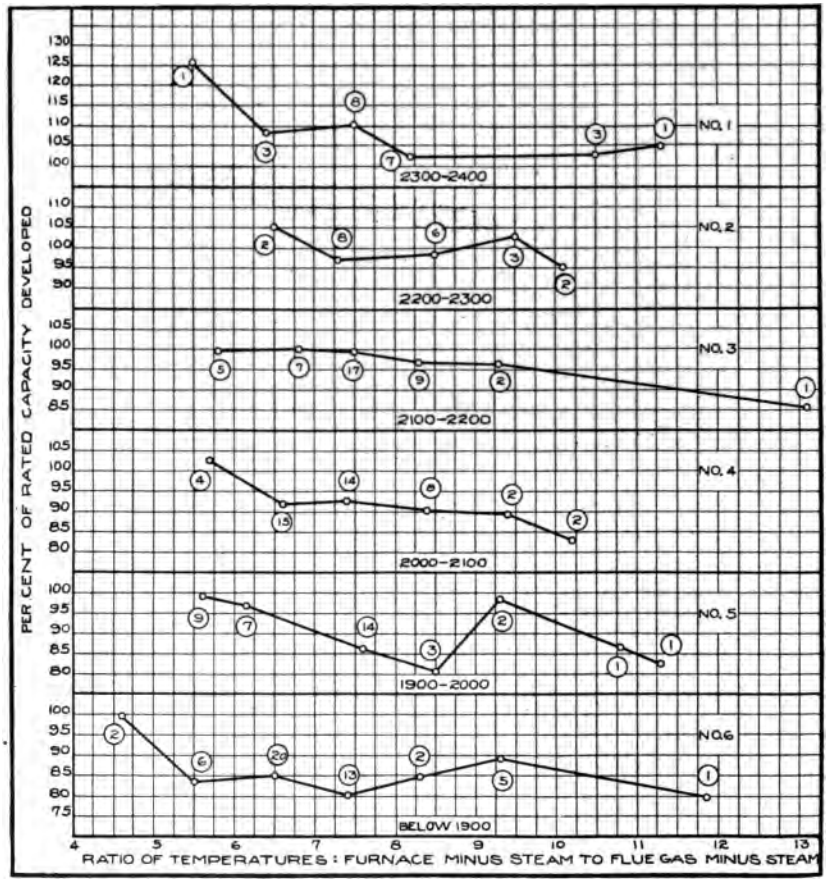


FIG. 63.—Relation between ratio of furnace temperature minus steam temperature to flue-gas temperature minus steam temperature and per cent of rated capacity, based on varying values of furnace temperature minus steam temperature.

The indication that the true boiler efficiency is so nearly constant *and so little affected* by initial furnace temperature is gratifying, as suggesting that some such formula as Perry's must be nearly correct. Thus encouragement is given to the hope that there is a way to determine once for all one constant boiler efficiency, from which we can calculate backward and obtain the combustion efficiency or per cent of completeness of combustion—the vital point in fuel testing. This applies only to boilers obtaining their heat by convection, not by radiation.

Fig. 63 is based on exactly the same data as those of fig. 62 (p. 133), which are elsewhere explained. It is intended to show the relation of flue-gas temperature to capacity when the furnace temperature remains nearly constant. The tests were arranged in six groups in such a way that the variation of the furnace temperature was less than 100° F. in each group.

The tests in each of these groups were then classified on the basis of the ratio of temperature of furnace minus that of steam to temperature of flue gas minus that of steam, and this ratio was plotted against the average capacity of each class.

The curves show a general tendency of the capacity to rise with the low-temperature ratios. This is in accordance with equation 17; as the furnace temperature remains nearly constant, higher capacities are obtained by increasing the weight of gases passing over the heating surface per second. The increase of the weight of gases causes, according to equation 17, the rise in flue-gas temperature.

In other words, this rise of flue-gas temperature is probably due to two causes: (1) When more heat is put through the outer gas film, soot, metal, scale, and inner steam film or bubbles the temperature gradient must necessarily be steeper, and since the conductivity of all these layers except the metal is low, the rise of temperature of the outer soot layer and its entangled gases may be several hundred degrees, whence it becomes a less active heat absorber, and consequently the gas escapes at a higher temperature, so that the efficiency of the boiler is less. (2) As shown in fig. 7 (p. 16), the circulation of water does not keep up to requirements, so that the steam film on the scale becomes thicker, or more of the surface is covered with bubbles, which again makes the boiler a poorer heat absorber.

A CONCEPTION OF BOILER AND FURNACE EFFICIENCY.

THE CODE FORM AND A REVISED FORM OF HEAT BALANCE.

The "boiler efficiency" given in the A. S. M. E. code as item 72* is the ratio of the heat absorbed in the boiler and carried away in the steam to the highest possible amount of heat that could be generated in the furnace. The denominator of this ratio is calculated by subtracting from the total pounds of "combustible" fired the number of pounds of combustible in the ash and multiplying this difference by the calorific value of 1 pound of "combustible."

The efficiency represented by code item 72* is, then, the over-all efficiency of the whole steam-generating apparatus, as combustible found in the ash is considered as if it had never been fired. It often happens that, on account of incomplete combustion, the quantity of heat represented by the denominator of the above ratio is not really developed in the furnace. Carbon monoxide in the analysis of the stack gases is one indication of this incomplete combustion.

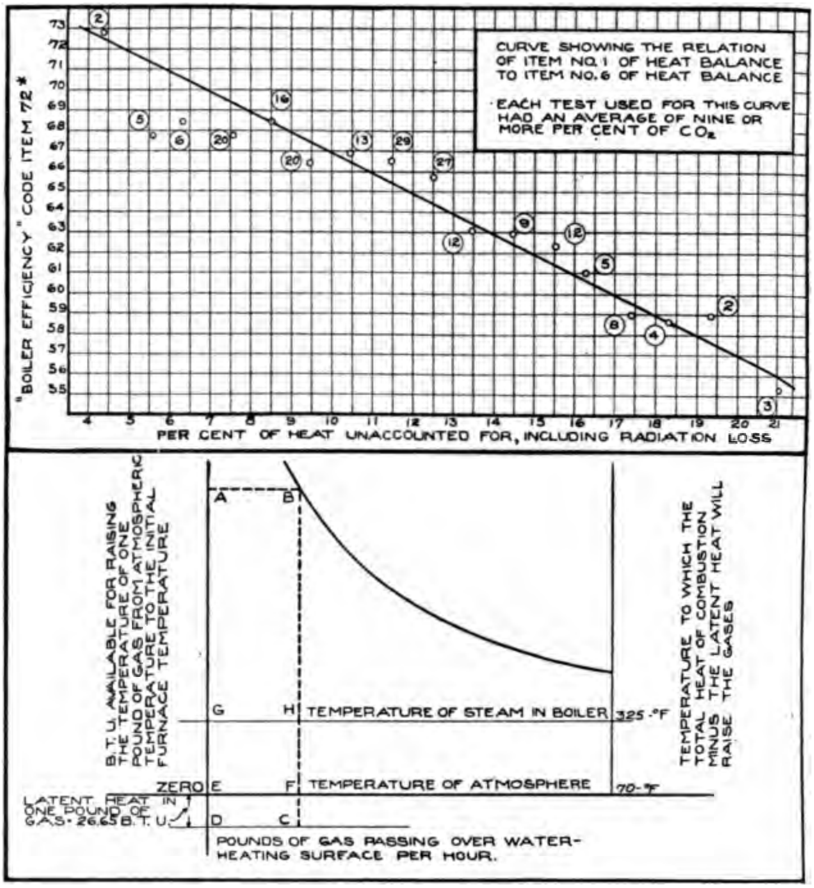


FIG. 64.—Relation of unaccounted-for loss, including radiation loss (upper curve) to boiler efficiency (code item 72*); and availability of heat to a boiler, as affected by changes in air supply to fuel (lower curve).

The ratio of the heat that is actually generated in the furnace to the maximum amount of heat that could be developed may be called the efficiency of the furnace or the furnace efficiency. The ratio of the heat absorbed by the boiler and carried away in steam to the heat actually generated from the burning of the fuel may be termed the boiler efficiency, and represents the ability of the boiler to absorb heat under given conditions. The efficiency given by code item 72* is the product of the boiler and furnace efficiencies as above defined.

Carbon monoxide is not the only resultant of incomplete combustion, although the heat lost by it is the only loss due to incomplete combustion that has been taken account of in the heat balance. The remainder of the incomplete combustion losses appear in the "unaccounted for." A high unaccounted-for loss, then, should be an indication of low furnace efficiency.

The upper curve of fig. 64 shows the relation between "boiler efficiency" (code item 72*) and the unaccounted-for loss plus radiation loss (heat balance, item 6). All the tests chosen for this chart have an average of 9 per cent or more of carbon dioxide in the escaping gases, which indicates that they must all have had comparatively high furnace temperatures. It has always been thought that when a high furnace temperature is maintained the boiler would absorb a high per cent of the heat developed in the furnace; therefore, the boiler efficiency as defined above must have been relatively high for all the tests of this chart.

It will be noticed that the sum of the ordinate and abscissa for any point of this curve is constant at 77 per cent. For instance, when item 72* is 73 per cent the unaccounted-for loss is 4 per cent; sum, 77 per cent. When item 72* is 57 per cent, the unaccounted-for loss is 20 per cent; sum, 77 per cent. The curve should have been drawn more nearly horizontal for the low unaccounted-for values.

The decrease of the combined efficiency of boiler and furnace (code item 72*) with the increase of the unaccounted-for loss must then be due to the decrease of furnace efficiency.

With this idea of furnace efficiency in mind, a new form of heat balance, shown below, is compared with the heat balance given in the A. S. M. E. code.

Heat balance as given in the code.

		Per cent.
1.	Heat absorbed by boiler	60.30
2.	Loss due to moisture in coal	.26
3.	Loss due to moisture formed by burning of hydrogen	4.09
4.	Loss due to heat carried away in dry chimney gases	14.96
5.	Loss due to incomplete combustion of carbon (CO loss)	2.17
6.	Loss due to unconsumed hydrogen and hydrocarbons, to heating the moisture in the air, to radiation, and unaccounted for	18.22

A revised form of heat balance.

1.	Heat absorbed by boiler	60.30
2.	Loss due to moisture in coal	.26
3.	Loss due to moisture formed by burning of hydrogen	3.26
4.	Loss due to heat carried away in dry chimney gases	11.93
5.	Loss due to radiation	3.97
	Total heat generated	79.72
6.	Loss due to incomplete combustion of carbon (CO loss)	2.17
7.	Loss due to other forms of incomplete combustion	18.11

In the new heat balance the subtotal 79.72 represents the per cent of the calorific value of the fuel that has been generated. It may be taken as the efficiency of the furnace, or, to speak more properly, the per cent of completeness of combustion. The latter phrase will be used in this discussion for this subtotal, which is defined as the ratio of the heat generated by burning a unit weight of combustible in the furnace to the heat obtained by burning the same weight of combustible in the calorimeter. This efficiency is designated elsewhere in this bulletin by the symbol E_3.

The method of determining the radiation loss is given on page 143. It is noticed that items 3 and 4 are smaller in the revised heat balance than in the heat balance of the code. This is because they have been multiplied by the per cent of completeness of combustion. This correction was made on the assumption that if only 79.72 per cent of the calorific value of the fuel was realized, only 79.72 per cent of each constituent of the moisture and ash-free coal was burned. This may not be the state of affairs in incomplete combustion, but the assumption furnishes a basis for calculations and perhaps the correction made on this assumption reduces the error of the calculation within the limits of accuracy of the analysis of the escaping gases.

In the revised heat balance the ratio of 60.30 to 79.72 is the boiler efficiency, which may be defined as the ratio of the heat absorbed by the boiler and carried away in the steam to the heat actually generated by the burning of the fuel. This ratio is elsewhere in this bulletin designated by the symbol E_5. The product of the furnace and boiler efficiencies is the efficiency of the boiler and furnace combined and is the same as that given in the code as item 72*. As explained above, this combined efficiency may be considered as the over-all efficiency of the steam-generating apparatus if the combustible in the ash is considered as not being fired.

As the calculations for these charts are somewhat lengthy, one test has been taken as an example and the calculations for it are given at the end of this discussion. The number of pounds of gas passing over the water-heating surface per hour and also the theoretical initial temperature of the gas have been calculated for each test. The term initial temperature is used in this paper to mean that temperature to which the gases would rise if it were possible to prevent loss of heat from them by either conduction or radiation until all combustion had ceased. In figuring the initial temperature it was assumed that the specific heat remains constant.

All the steaming tests made at the testing plant were arranged in groups according to per cent of rated capacity, as follows: 65 to 75, 75 to 85, 85 to 95, etc. Then the tests of each of these groups were rearranged according to their calculated initial temperatures into the llowing groups: 1,600° to 1,800° F., 1,800° to 2,000° F., 2,000° to ,200° F., etc. Each of these 40 smaller groups was averaged for 1) initial temperature (calculated); (2) pounds of gas passing over e water-heating surface per hour; (3) percentage of rated capacity eveloped; (4) boiler efficiency (E_5), and (5) true boiler efficiency E_4). The first four averages for each group were considered as

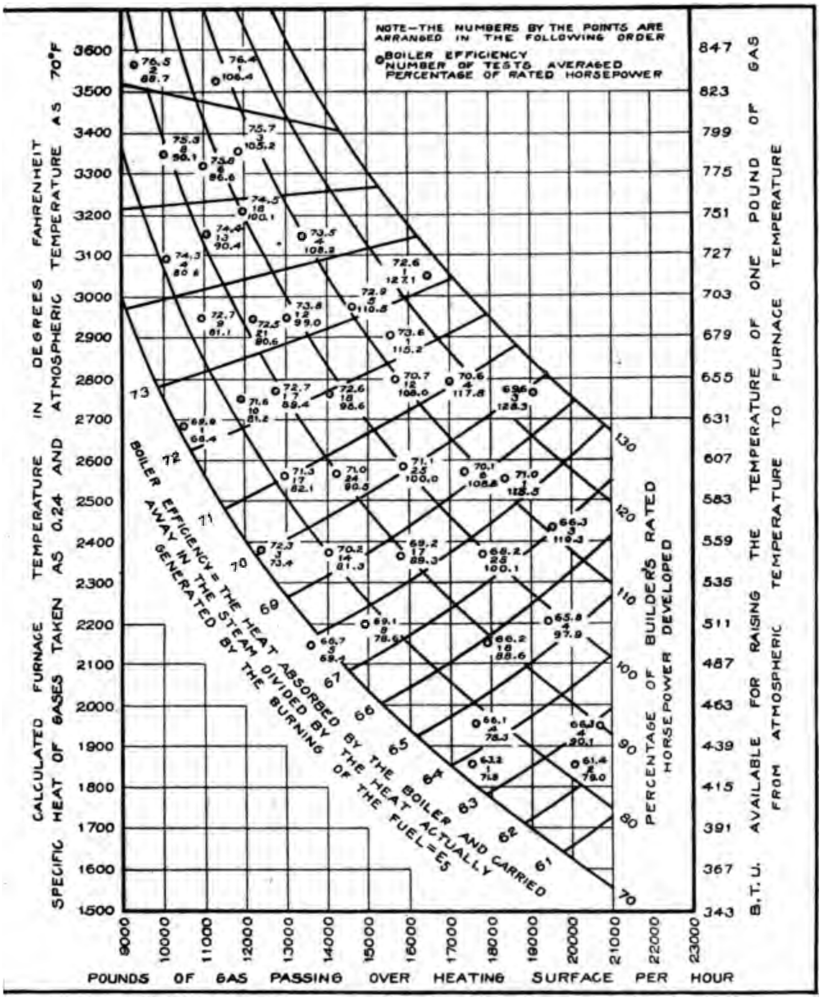


FIG. 65—Curves of constant boiler efficiency (E_5) and of constant capacity developed.

ata of one representative test and were plotted on the chart shown fig. 65, and the first three and the fifth in fig. 66.

DERIVATION OF THE CONSTANT-CAPACITY CURVES OF FIG. 65.

Each of the above forty representative tests was plotted on rec- angular axes, the theoretical temperatures being used as ordinates ee fig. 65) and the number of pounds of gas passing over the water-heating surface per hour as abscissas. When a point was located it was marked with the average capacity, the number of actual tests that were averaged, and the average boiler efficiency E_5. (See note at top of the chart.) In the upper left-hand corner there is a point which is marked "76.5, 2, and 88.7." This means that two tests were averaged, that the average E_5 was 76.5, and that the average capacity was 88.7 per cent of the builder's rated capacity; and the position of the point on the chart shows that the average number of pounds of gas passing over the water-heating surface per hour was 9,300. When the forty representative tests were plotted in this manner it was found that lines of constant capacity could be drawn through these points. The lines extending from the upper left-hand corner to the lower right-hand corner of the chart are these constant-capacity lines. They are labeled with their respective percentages of rated capacity developed.

DERIVATION OF BOILER EFFICIENCY (E_5).

Moisture is always present in the products of combustion, and it takes an appreciable amount of the heat generated in the furnace to convert this from water into steam. The rest of the heat generated goes to raising the temperature of the gases. It was found that the average amount of latent heat in 1 pound of the escaping gases was 26.65 B. t. u., which is enough to raise the temperature of 1 pound of gas 111° F. In these calculations the specific heat of the dry gases was taken as 0.24 for all temperatures and the specific heat of steam as 0.48. On this assumption the same amount of heat is used to raise the temperature of 1 pound of steam 1° as is required to raise the temperature of 2 pounds of dry gases 1°, so in order to use 0.24 as the specific heat of all the products of combustion the number of pounds of steam in the gases was multiplied by 2.

Let the lower curve of fig. 64 (p. 138) be one of the constant-capacity curves shown in fig. 65. The scale to the left of the chart represents the B. t. u. available for raising the temperature of 1 pound of gas from atmospheric to furnace temperature. The theoretical furnace temperatures to the right of the chart are obtained by dividing by 0.24 the B. t. u. available for raising the temperature of 1 pound of gas and adding to the quotient the temperature of the atmosphere, which is taken as 70° F. The line CD is drawn in such a manner that the distance ED represents on the scale to the left 26.65 B. t. u., which was found to be the average amount of latent heat in 1 pound of furnace gas. The area ABCD represents the total heat generated in the furnace; the area CDEF shows the latent heat in the gases and the area ABEF shows the heat available for raising the temperature of EF pounds of gas from 70° F. to the initial furnace temperature A. Since the curve is one representing constant capacity, the heat absorbed by the boiler in all tests on this curve will be a constant and this constant divided by the area ABCD will be the boiler efficiency E_5 for the point B. By using the ratio of the constant heat absorbed by the boiler to the area ABCD, those positions of B which represent efficiencies 61, 62, and 63 per cent, etc., were found. By this means lines of constant-boiler efficiency (E_5) were found and drawn on the chart (fig. 65). It will be noticed that the efficiency of the plotted points generally falls within about 1 per cent of their allotted position as determined by these constant-efficiency lines.

DERIVATION OF TRUE BOILER EFFICIENCY (E_4).

The constant-capacity lines are of the form $xy^n = \text{constant}$, where x = number of pounds of gas passing over the water-heating surface per hour and y = the calculated initial temperature. The curves are all asymptotic to the lines $x = 0$ and $y = 325°$ F. (See fig. 64.) The temperature of the steam in the boiler at about 80 pounds pressure is 325° F. Now, if the boiler were infinitely long and there were no heat lost in radiation, the boiler could never cool the gases below a temperature of 325° F. In other words, only the heat represented by the area ABGH is available to the boiler. The ratio of the heat absorbed by the boiler and carried away in the steam (which is constant for any point on the constant-capacity line) to the heat available for the boiler, area ABHG, has been termed the true-boiler efficiency (E_4). (This definition of E_4 differs very slightly from the one finally chosen, for which see glossary, p. 182.)

This efficiency E_4 has been calculated for each test and the method used is shown with the other calculations on page 145. The chart shown in fig. 66 is similar to that of fig. 65 in every respect except that E_4 is used instead of E_5.

METHOD OF ESTIMATING RADIATION.

It was necessary to devise some method for estimating the radiation losses in order to calculate the per cent of completeness of combustion (E_3). The method used was very crude and was based on the following reasoning:

The radiation from the top of the boiler drum and the front and rear water legs is very nearly constant and was determined as follows: With no fire under the boiler the uptake was closed by laying boards across the opening at the base of the stack and covering them with cement. This prevented any air from going up the stack. The fire doors and ash pit were bricked up to prevent air from entering the setting. After drawing the water out of the boiler it was filled with steam from another boiler carrying 80 pounds pressure. This pressure was maintained until the temperature in the combustion chamber became constant. The amount of condensed steam per hour was then weighed and was taken as a measure of the heat radiated per hour. The radiation from the brick setting and fire doors was considered to increase with the capacity. When the boiler developed 90 per cent of its rated capacity the variable radiation was taken as three-fifths and the constant radiation as two-fifths of the total heat radiated. The increase of the variable radiation with capacity was such as to

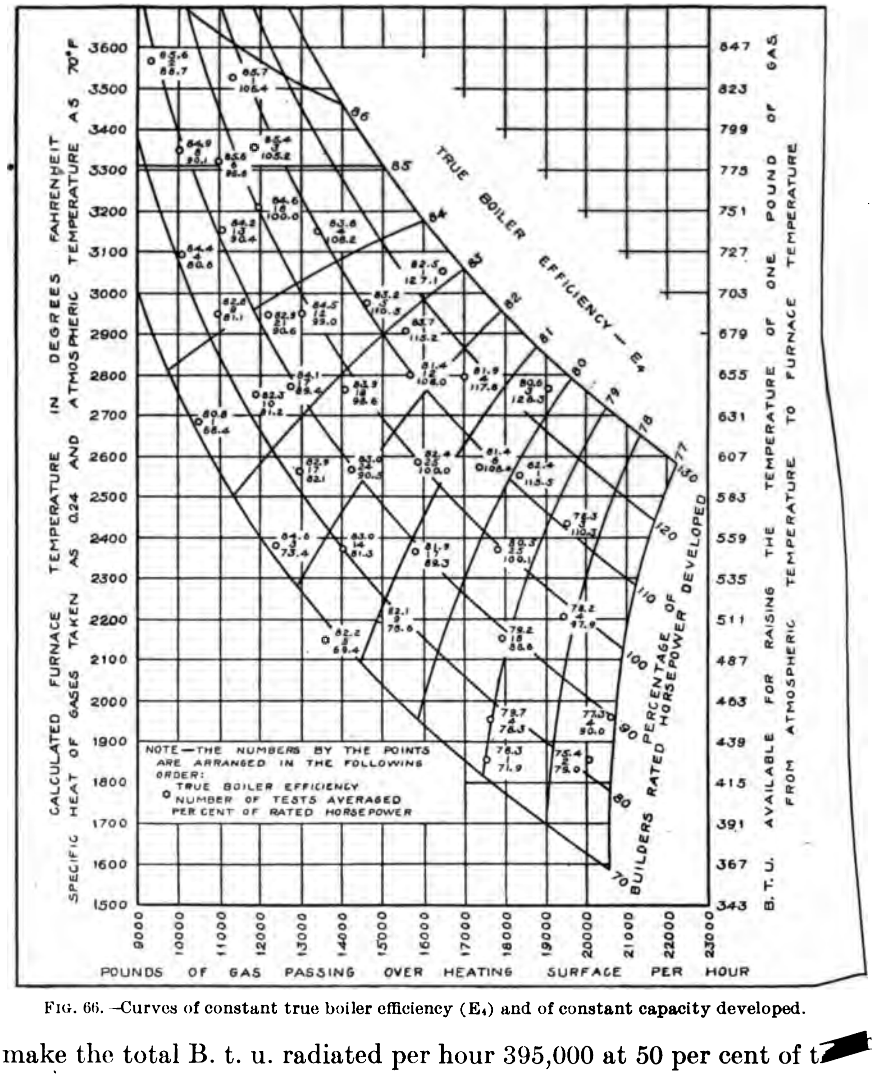


FIG. 66.—Curves of constant true boiler efficiency (E_4) and of constant capacity developed.

make the total B. t. u. radiated per hour 395,000 at 50 per cent of t
rated capacity and 500,000 B. t. u. at 120 per cent of the rated capa
ity. A chart (not given here) was drawn having B. t. u. radiated p
hour as ordinates and per cent of the rated capacity developed
abscissas, and the two above points were plotted on it. By connec

ng these points with a straight line the B. t. u. radiated per hour ould be estimated for any capacity.

The heat required to change 1 pound of water at 70° F. to steam at 212° F. = $(212-70)\times1+966=142\ (0.48+0.52)+966=(0.48\times142)+(0.52\times142)+966=68+74+966=68+1{,}040$.

The heat required to raise 2 pounds of dry gas from 70° F. to 212° F. = $(212-70)\times0.24\times2=68$.

It is evident from the above that 1,040 more B. t. u. are required to change 1 pound of water from 70° F. to steam at 212° F. than are required to raise 2 pounds of gas through the same range of temperature. However, at any temperature above 212° F. the same amount f heat is required to raise the temperature of 2 pounds of gas 1° F. s is required to raise the temperature of 1 pound of steam 1° F. herefore in calculating the total heat and the initial temperature of he gases, 1 pound of water may be considered as the equivalent of 2 ounds of dry gas, provided that in the case of the 1 pound of water ccount is taken of the 1,040 B. t. u. which are not available for raisng temperature.

The following calculations were made on test 216, the heat balance f which is given on page 139:

Calculations based on test 216 to deduce a better heat balance.

er cent of completeness of combustion (E_3):		Per cent.
	Per cent of rated capacity developed	103
	Calorific value of 1 pound of "combustible" taken as	100
A.	Heat absorbed by boiler (heat-balance item 1)	60. 30
B.	Heat carried away in moisture of coal (heat-balance item 2)	. 26
C.	Heat carried away in moisture formed by burning hydrogen (heat-balance item 3)	$(4.09 \div 100 \times E_3)$
D.	Heat carried away in dry gases (heat-balance item 4)	$(14.96 \div 100 \times E_3)$
E.	Heat lost in radiation	3. 97
E_3	(per cent of calorific value of fuel that has been generated) $=A+B+C+D+E$	79. 72
	Boiler efficiency (E_5) $=A\times100\div E_3$	75. 64
Total pounds of equivalent dry gas passing over water-heating surface per hour:		Pounds.
F.	Moisture in coal for every pound of "combustible" (figured from proximate analysis)	0. 03
	Hydrogen per pound of "combustible" (ultimate analysis)	. 0543
G.	Moisture formed by burning of hydrogen $=9\times0.0543\times E_3$	. 39
H.	Total moisture in gases formed from 1 pound of "combustible" $=F+G$	. 42
	Dry gas per pound of "combustible," assuming $E_3=100$ (figured from gas analysis)	18. 35
I.	Actual dry gas per pound of "combustible" as fired $=18.35\times E_3$	14. 63
J.	"Equivalent" dry gas per pound of "combustible" as fired $=I+(2\times H)$ (see discussion of calculations)	15. 47
	Total combustible ascending from grate per hour (code item 47*)	775. 0
	Total equivalent dry gas passing over the water-heating surface per hour $=15.47\times775.0$	11, 990

	B. t. u.
Heat in gases below 325° F. (steam temperature):	
K. Heat in the gases, from 1 pound of "combustible," which is unavailable for raising temperature=H × 1,040 (see discussion of calculation)..	437
L. Heat required to raise the temperature of gases formed from 1 pound of "combustible" taken from 70° F. to 325° F.= J × 612..........	947
M. Total heat below 325° F. in the gases from 1 pound of "combustible"=K+L..	1,384
Heat above 325° F. in the gases from 1 pound of "combustible"—that is, heat available to the boiler:	
Calorific value of 1 pound of "combustible" (item 51).............	15,423
N. B. t. u. generated from 1 pound of "combustible"= $E_3 \times 15,423$....	12,295
O. Heat available for the boiler per pound of "combustible"=N—M...	10,911
True boiler efficiency (E_4):	
P. Heat absorbed by the boiler per pound of "combustible" (from heat balance)..	9,300
$E_4=P \div O=85.23$ per cent.	
Theoretical initial temperature:	
Heat above 325° F. in 1 pound of gas=O ÷ J..........................	705.3
705.3 B. t. u. will raise the temperature of 1 pound of gas 705.3 ÷ 0.24, or 2,939° F.	
Initial temperature = 2,939° + 325° = 3,264° F.	

As explained in the discussion on page 140, the calculated initial temperature as given by the scale to the left of figs. 65 (p. 141) and 66 (p. 144) is that temperature to which the gases would rise provided no heat were lost by conduction or radiation until combustion had ceased, 0.24 being used as the specific heat of the gases at all temperatures. However, these conditions never exist in practice. A large amount of heat is lost from the gases by both conduction and radiation before combustion ceases; furthermore, the specific heat of the gases at high temperature may be higher than 0.24. For these reasons the calculated furnace temperature is much higher than that actually attained.

In order to obtain a calculated initial temperature of 3,480° F., it is necessary to have an average of about 12.5 per cent of CO_2 in the escaping gases and to burn a coal of about 14,000 B. t. u. per pound of dry coal. This temperature is about the highest that could be obtained by a hand-fired furnace. If it were possible to maintain a completeness of combustion of 100 per cent at this temperature the efficiency of the boiler (72*) would be 76 per cent, which is the highest over-all efficiency attainable. (See fig. 65.)

PLOTTING OF PROBABILITY CURVES.

After having obtained the values of furnace and true boiler efficiencies as explained on pages 143–145, the true boiler efficiencies were arranged in groups according to their values, and the number of each group was plotted according to its magnitude as shown in the upper curve of fig. 67, called the probability curve. (See p. 158.) If a line be drawn through these points a curve results quite as symmetrical on both sides as a probability curve and shaped very much like it.

The lower curve of fig. 67 is a similar plotting of the number of efficiency 72* values for the same tests falling within each group, the curve being drawn through the points. It lacks the symmetry of the upper curve, and the points do not fall so near the peak. The symmetry of the upper curve and its similarity to a mathematical probability curve suggest that the true boiler efficiency (E_4) is much more nearly constant than efficiency 72*, and that the attempt made to find a constant true boiler efficiency is along the right track. But the curves of fig. 66, discussed on page 143, show that this "constant" true boiler efficiency is subject to variations when capacity and furnace temperature are changed, although they are comparatively slight. By referring to the upper curve of fig. 67, it will be seen that most of the tests fall between 77 and 87 per cent, the greater number being close to 83.7 per cent, the position of the peak. This means that under average conditions the boilers at the fuel-testing plant will absorb about 83.7 per cent of the heat available to them.

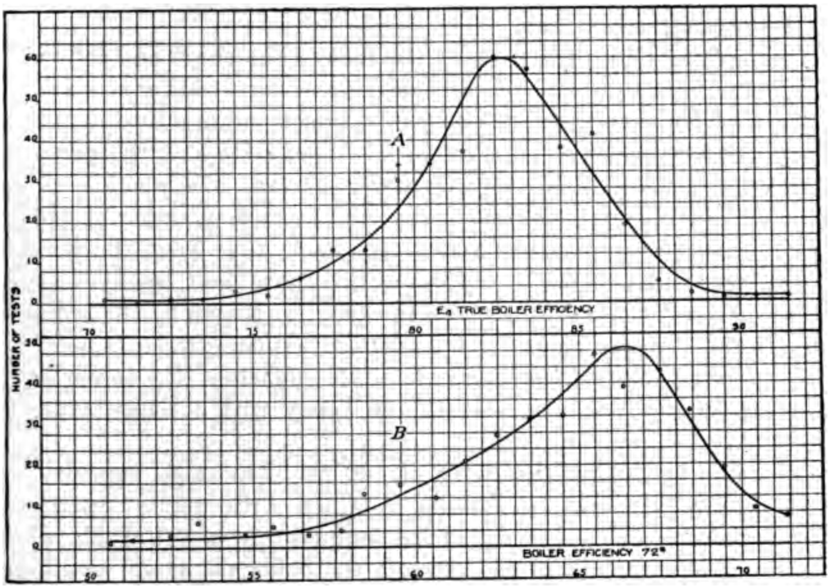


FIG. 67.—Probability curves: *A*, Approximate curve based on true boiler efficiency; *B*, attempt at approximate curve based on boiler efficiency 72*. Tests 89–401.

The meaning of constant-capacity curves for boiler efficiency (E_5) could perhaps be made plainer by taking from the chart (fig. 65, p. 141) four specific examples:

Example 1. Taking the furnace temperature at 2,500° F., and moving from left to right on the chart, we cut lines of higher capacity and lower boiler efficiency (E_5); with a capacity increase from 70 to 120 per cent, the boiler efficiency drops from. 71 to 67 per cent. Inasmuch as the furnace temperature remains constant the quantity of heat received by the lower row of tubes by conduction through the encircling tiles and by radiation from the hot brickwork is perhaps the same. Therefore the decrease in boiler efficiency must be charged to the tubes which are farther from the furnace and receive their heat from the gases by convection and conduction.

A possible explanation of lower boiler efficiencies with higher capacities is that a steeper temperature gradient is required to transmit more heat through the soot, metal, and scale. There is also a thicker layer of steam bubbles on the heating surface, which increases the resistance to the passage of heat. These effects cause the flue gases to leave the heating surface of the boiler at higher temperatures as the capacity increases.

Example 2. Using the scale at the foot of the chart and following the line of 15,000 pounds of gas passing over the heating surface per hour, we find that with a calculated furnace temperature of 2,100° F. the boiler efficiency (E_5) is about 67 per cent and the capacity about 70 per cent. Moving vertically upward the pounds of air must be slightly reduced and more coal burned in order to obtain higher furnace temperature and at the same time keep the pounds of gas per hour constant. By doing this more heat becomes available for raising the temperature of the gases, as shown by the ordinate on the right of the chart. At a furnace temperature of 3,300° F., the capacity is 130 per cent and the boiler efficiency (E_5) 75 per cent, an increase of 8 per cent over the efficiency with a temperature of 2,100° F.

Example 3. Taking the curve of 100 per cent rated capacity we find that rated capacity can be obtained with many conditions. The first extreme is with a furnace temperature of 2,100° F., when passing 21,000 pounds of gas through the boiler per hour; obtaining a boiler efficiency (E_5) of 64 per cent. The second extreme is with a furnace temperature of about 3,500° F., and a boiler efficiency of 76 per cent, when passing about 11,000 pound of gas through the boiler per hour.

Example 4. A boiler efficiency of 70 per cent can be attained under many conditions. The lowest temperature on the chart with which this efficiency can be obtained is 2,400° F. at a capacity of 70 per cent, when passing about 12,000 pounds of gas through the boiler per hour. In order to maintain this high efficiency when working at 130 per cent of rated capacity, it is necessary to increase the furnace temperature to 2,800° F. by burning more coal with decreased air supply.

The curves of fig. 66 (p. 144) differ from those of fig. 65 (p. 141) in that true boiler efficiency (E_4) is used instead of boiler efficiency (E_5). The true boiler efficiency is based on the heat available to the boiler, considering only that part of the heat in the gases as available which is above the temperature of the steam. If the steam and water in the boiler were at atmospheric temperature, the two efficiencies, E_5 and E_4, would be the same; but as the temperature of the water in the boilers is always from 150° to 200° F. above the atmospheric temperature less heat is available for the boiler.

The general significance of the chart is (1) that true boiler efficiency increases with initial temperature, perhaps because an increasing amount of heat is absorbed by the lower row of tubes on account of conduction through the encircling tiles and of radiation on them, where they are bare in the rear, from the brickwork of the combustion chamber, and also because the higher temperature of the gases causes a steeper temperature gradient through the soot, metal, and scale, so as to cause a higher rate of flow of heat. All these causes are apart from the simplest statement of Perry's suggested theory of constant true boiler efficiency and are modifying factors of it in practice. The further general significance of this chart is (2) that at the same initial temperature the true boiler efficiency decreases as the mass of gases passed over the heating surface increases—that is, as the capacity increases. The explanation of the fact that the true boiler efficiency (E_4) is lower with these conditions is that inasmuch as capacity is proportional to the rate of heat absorption by the boiler the temperature difference between the water in the boiler and the first layer of gases on the outside must be greater in order that more heat be transmitted into the water in the same length of time. This increase in the temperature gradient causes the gases to leave the heating surface of the boiler at a higher temperature than in the cases of low capacity. The efficiency range of this chart is not very large—only from 77 to 85 per cent—and few points are near the extremes.

MISCELLANEOUS.

RELIABILITY OF OBSERVATIONS AND DATA.

The following remarks are given to facilitate the utilization of the actual data of the tests which are discussed in this volume:

Item 2: Duration of trial. This item is important for its effect on the water level in the boiler, which is easily changed several inches by opening or closing the steam valve, or by starting or stopping a large engine. Perhaps the usual error on this account was a fraction of 1 per cent of the evaporation. The item also enters into the errors of estimating the amount of fuel on the grate at starting and stopping. This estimating was always done with care, but the error on ten-hour tests may have been sometimes as much as 1 per cent of the coal burned, especially if the amount was small. As regards the fuel, when estimating accuracy, the real question is, How much coal was burned? not, How long did the test last?

Item 3: Grate surface, square feet. Boiler No. 1 was equipped with a plain grate, having an area of 40.55 square feet. Boiler No. 2 was equipped with a McClave rocking grate, having an area of 36.4 square feet. These areas were maintained constant during the 1905 tests.

Item 11: Barometer, inches of mercury. This observation was always obtained from the Weather Bureau, and no correction was made for difference in elevation between the Weather Bureau station and the fuel-testing plant, which was only a few feet.

Item 11.1: Steam pressure. This reading was sometimes taken from a calibrated steam gage and sometimes from a recording-instrument chart. It is correct within a pound.

Items 12 and 13: Draft readings. These readings are accurate to 0.02 inch.

Item 16: Temperature of fireroom. Correct within 2°.

Item 17: Temperature of steam, calculated.

Item 18: Correct unless otherwise noted.

Item 20: Correct unless otherwise noted.

Item 21: Generally low, owing to air leakage, and apt to be in error in extreme instances, as much as 100° F., this error being the aggregate of the thermometer error and the greater error due to the difficulty of obtaining a true average temperature in the stack by the use of a single thermometer. Large errors are noted in their respective tests.

Item 21.1: Average temperature of furnace. Read by means of a Wanner optical pyrometer. All observations were made looking into the combustion chamber, about 2 feet from the rear end, 1 foot below the tile roof. When looking at flame, as was generally the case, the indications were perhaps well within 200° F. of the right value, generally perhaps within 100° F., although this is merely an estimate based on circumstantial evidence. In the absence of flame, light was received from the opposite wall, which was plainly cooler than the gases, as was evident on comparing it by eye with the tile roof near by; and even this latter was cooler than the gases which heated it, because heat was constantly passing upward through the tile into the water tubes. How much too low such readings are is only a guess—perhaps 100° to 200° F. In general, the tests on coals high in "fixed carbon" have combustion-chamber temperatures too low.

Item 28: Total weight of ash and refuse. Refuse was taken to mean everything which fell through the grate plus the ash and clinker pulled out of the furnace during cleaning of fire. It is noteworthy that the weight of earthy matter in the refuse from a test is usually 15 or 20 per cent short of the amount that the chemical analysis indicates; the difference undoubtedly goes over into the combustion chamber and up the stack.

Item 32: Fixed carbon of proximate analysis.

Item 33: Volatile matter of proximate analysis.

The preceding two items are based on arbitrary methods of driving off the so-called "volatile matter" and weighing the remainder to get ash and fixed carbon. By varying the standard of conditions under which the distillation is effected very different results can be obtained, and thus it may be seen that care should be exercised in deducing results of practical trials from the purely arbitrary results obtained from proximate analyses of dry or moist coal. A greater number of ultimate analyses should customarily be made, inasmuch as they furnish absolute data. Coal molecules are probably complex, and although little is known on the subject it is likely that the products and even the amounts of products of destructive distillation vary widely with the method followed, as to temperature, rapidity of heating, etc.

Item 34: Percentage of moisture in coal. This item is uncertain at best. It is probable that on warm, dry, and windy days the coal lost some moisture while being quartered on the floor of the boiler room, so that the coal fired was really lower in heating value than the chemical analysis indicates.

Items 37, 38, 39, 40, 41, and 42: Ultimate analysis of dry coal. Furnished by the chemical division.

Items 50 and 51: Furnished by the chemical division. These items were used in test calculations in preference to items 52 and 53.

Items 54 and 56: These items are untrustworthy in these tests; concordant results were never obtained. All the investigational work done on the matter pointed to the possibility that eddies vitiated the readings, because the vertical section of pipe in which the sampling nipples were placed was only 2 feet long. These items are probably not reliable within 50 per cent of the values given.

Item 77: Percentage of smoke. Dense black (so estimated) taken as 100 per cent.

Item 81: Average thickness of fire. Only approximate, because of difficulties of measurement when flame is present. It also varies with the personal equation of the observer.

Items 84, 85, 86, 87, and 88: These items are somewhat in error, owing to air dilution.

Heat balance: Items 2 and 3, very nearly correct; item 4, usually doubtful, owing to inaccurate flue-gas temperatures; item 5, only approximate; item 6, doubtful—results of our tests show that the unaccounted-for loss and the flue-gas loss up the stack take and give reciprocally. (See fig. 35, p. 63.)

The chart shown in fig. 68 indicates that in general terms the unaccounted-for heat increases in percentage with the loss due to CO.

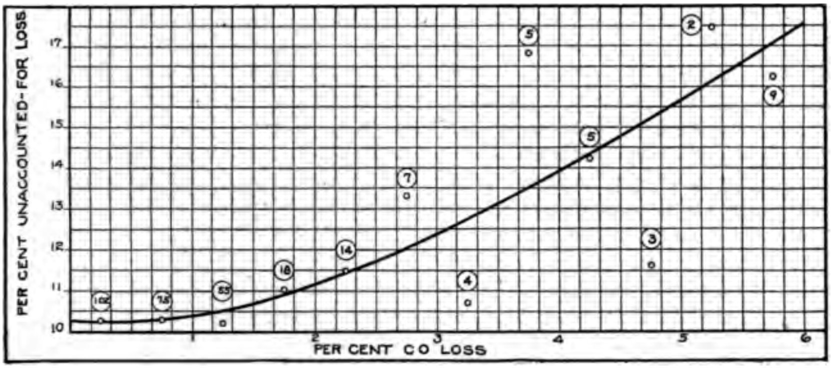


FIG. 68.—Relation of unaccounted-for loss to CO loss (tests grouped on basis of per cent of CO loss).

COMPUTATIONS OF A STEAMING TEST.

The data necessary for complete results of a steaming test come from three sources: (1) The boiler room, (2) the chemical laboratory, and (3) the United States Weather Bureau.

After a coal has been tested, from ten days to two weeks are required for the chemical work to be completed before definite results are known. The state of weather, the barometric pressure, and the relative humidity for the day of the test are obtained from the Weather Bureau.

The computed results given in this report have been calculated according to the methods indicated in the A. S. M. E. code for making boiler trials. However, it has been thought advisable to explain how several of the items were obtained or determined, and in doing this, for brevity, code numbers will be used.

Item 23: See explanation under "Average diameter of coal," p. 45.

Item 27=item 25×(100—item 34).

Item 28=total ash and *refuse* from test. This includes the coal which falls through the *grate.*

Item 29: In most tests the ash which was pulled from the grate when cleaning fires was called clinker unless the ash which formed on the grate was all free ash. Then the per cent of clinker is this weight figured as a percentage of item 28.

Item 30=item 27−item 28.

Item 30*=item 25×(item 32+item 33)−(item 28×item 44).

Item 31=item 28÷item 27.

Item 32a=item 32÷(item 32+item 33).

Item 33a=item 33÷(item 32+item 33).

Items 37a, 38a, 39a, 40a, 41a are determined by dividing items 37, 38, 39, 40, and 41 by (100−item 42).

Item 46=item 27÷item 2.

Item 47=item 30÷item 2.

Item 47*=item 30*÷item 2.

Item 48=item 46÷item 3.

Item 49=item 47÷(item 7=2,031).

Item 49*=item 47*÷(item 7=2,031).

Item 51=item 50÷(100−item 42).

Item 54, obtained by separating calorimeter.

Item 56, "quality of steam," found by subtracting item 54 from 100. In boiler use this value must be corrected, and it is the corrected value that we have used for this item.

Extract from the A. S. M. E. code for making boiler trials: "The factor of correction for quality of steam in a boiler test differs from the quality itself from the fact that the temperature of the feed water is lower than that of steam." In using quality of steam, as given by the calorimeter, therefore we lose the heat required to raise the temperature of the moisture in steam to steam temperature. The method of determining the factor of correction for quality of steam is given below:

Q=quality of moist steam as given by calorimeter.

P=the proportion of moisture in steam.

F=the factor of correction for the quality of the steam when the steam is moist.

H=the total heat of the steam due to the steam pressure.

T_1=the total heat in the water at the temperature due to the steam pressure.

J_1=the total heat in the feed water due to the temperature.

$$F=\frac{Q\,(H-J_1)+P\,(T_1-J_1)}{H-J_1}=Q+P\left(\frac{T_1-J_1}{H-J_1}\right)$$

Item 57: This is corrected for inequality of water level and of steam pressure at beginning and end of test.

Item $60=\frac{H-h}{965.7}$, in which H and h are, respectively, the total heat in steam of the average observed pressure, and in water of the average observed temperature of the feed. The difference between H and h gives the heat absorbed. The 965.7 is the heat of vaporization at 212° F. Dividing H−h by 965.7, we obtain a factor which we can use as a multiplier to reduce pounds of water fed to boiler to pounds of equivalent water.

Item 61=item 57×item 56×item 60.

Item 65=item 63÷34.5 (34.5 pounds water evaporated per hour into dry steam from and at 212°, equals 1 boiler horsepower).

Item 68=item 57÷item 25.

Item 69=item 61÷item 25.

Item 70=item 61÷item 27.

Item 71=item 61÷item 30.

Item 71*=item 61÷item 30*.

Item 72=item 71×965.7÷item 51. This is the efficiency of the furnace and boiler combined, figured from pounds of combustible apparently ascending from the grate.

Item $72^* = \text{item } 71^* \times 965.7 \div \text{item } 51$. This is the efficiency of the furnace and boiler combined, figured from pounds of combustible actually ascending from the grate.

Item $73 = \text{item } 70 \times 965.7 \div \text{item } 50$. This is the efficiency of the furnace, boiler, and grate. It is usually styled over-all efficiency.

Item 77: Smoke readings were taken by using the Ringelmann charts. To obtain this item the sum of the readings was multiplied by 20 and this result divided by the total number of readings.

Item 81: Estimated by expert in charge of fire.

Item 82: The fire was considered to be in normal condition from the start of the test until the close, except during cleanings. The time for cleaning is subtracted from the length of the test and the result divided by the number of firings.

Item 83: This is the interval between raking, slicing, and cleaning the fire.

The following items are from the heat balance or distribution of the heating value of the combustible:

Total heat value of 1 pound of "combustible," B. t. u.—item 51.

Item $1 = \text{item } 71^* \times 965.7$ (evaporation from and at 212° F. per pound of "combustible" ascending from the grate$\times 965.7$).

Item $2 = \text{item } 34 \div (\text{item } 32 + \text{item } 33) \div 100 \times [(212 - t) + 965.7 + 0.48\,(T - 212)]$. This operation consists in referring the moisture to "combustible," raising the temperature to 212° F., evaporating it, and then superheating to stack temperature. The specific heat of superheated steam was taken as 0.48. t=temperature of air in the boiler room, T=temperature of the flue gases.

Item $3 = \text{item } 38a \div 100 \times 9 \times [(212 - t) + 965.7 + 0.48\,(T - 212)]$. This operation assumes all the hydrogen burned to water. The temperature of the water is raised to 212° F. and the water is evaporated and then superheated to stack temperature.

$$\text{Item } 4 = \frac{11 \times \text{item } 84 + 8 \times \text{item } 85 + 7\,(\text{item } 86 + \text{item } 88)}{3\,(\text{item } 84 + \text{item } 86)} \times \frac{\text{item } 37a}{100} \times 0.24 \times (T - t).$$

t=temperature of air in boiler room; T=temperature of the flue gases. The above operation consists in figuring the pounds of dry chimney gases per pound of carbon; this value, multiplied by the per cent of total carbon in the combustible, gives pounds of dry chimney gas per pound of combustible; this number of pounds of gas is then heated from the temperature of inside air to stack temperature at a constant specific heat of 0.24.

Item $5 = \text{item } 86 \div (\text{item } 84 + \text{item } 86) \times \frac{\text{item } 37a}{100} \times 10{,}150$. The quantity 10,150 is the number of B. t. u. generated by burning to carbonic acid 1 pound of carbon contained in carbonic oxide.

Item $6 = 100 - (\text{items } 1 + 2 + 3 + 4 + 5)$.

DISSOCIATION CURVES OF CARBON DIOXIDE AND WATER VAPOR.

The curves of fig. 69 are probably self-explanatory. It should be stated that the data were experimentally obtained and calculated in 1905 or 1906 by Professors Nernst and Wartenberg, two men of the highest competency. As an example, using curve No. 1, 0.051 per cent of water vapor (about 0.05 per cent) at atmospheric pressure is dissociated into hydrogen and oxygen. These data are probably the most reliable extant. They indicate that many fears heretofore widely held, as to limitations in high-temperature work due to dissociation, are almost groundless.

It will be noticed that the per cent dissociation of CO_2 increases more sharply at about 1,300° C. than anywhere else. On referring to fig. 14 (p. 23), giving the percentage of CO as a function of combustion-chamber temperature, it will be noticed that the sharpest curvature of the CO curve is at about 2,600° F. (about 1,420° C.), which is not far from 1,300° C.

Now comes in the vital factor of furnace practice. In order to get higher temperatures the air supply must be reduced; and less oxygen means poorer combustion, as discussed under "Mass action" (p. 170). Thus high temperatures are associated with incompleteness of combustion, shown in figs. 14 (p. 23) and 31 (p. 51).

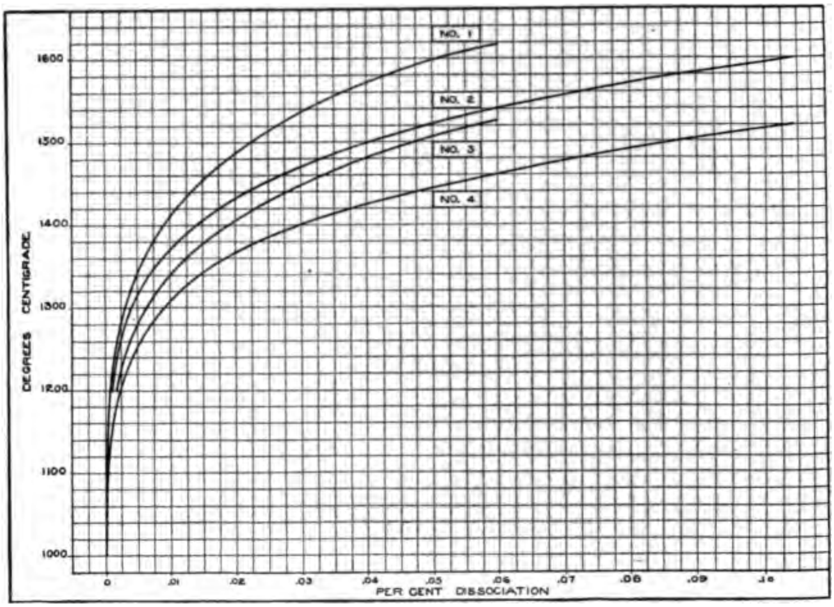


FIG. 69.—Dissociation curves of water vapor and carbon dioxide: Curve No. 1, H_2O at atmospheric pressure; No. 2, CO_2 at atmospheric pressure; No. 3, H_2O at 0.1 atmospheric pressure; No. 4, CO_2 at 0.1 atmospheric pressure. Data from Zeitschrift für physikalische Chemie, vol. 56, No. 5, 1906.

WATER-JACKETED GAS SAMPLER.

Fig. 15 (p. 24) shows a water-jacketed gas sampler, consisting of a 1¼-inch pipe closed at each end with a cap and two ¼-inch pipes. The gas is drawn through one of the ¼-inch pipes, which passes through both the caps as indicated in the figure. The other ¼-inch pipe brings cold water into the large pipe. The ¼-inch nipple, fitted into the same end of the large pipe as that at which the water enters, serves as a water outlet. The water used for cooling the sampler is obtained from the city mains. The only difficulty ever experienced in the use of the sampler was when the city pressure was suddenly reduced.

Probably the gas drawn through this sampler would be more truly representative of the actual composition of the hot gases in the furnace if the opening from the furnace into the water-jacketed passage were smaller. The internal diameter of a ¼-inch pipe is about three-eighths of an inch. Probably it would be better to use a brass pipe of very small bore, say ⅛-inch. The object of having the gases enter a small-bore pipe would be to cool them suddenly so as to permit no combustion while they were being cooled. Still it is not likely that any serious error is introduced by using pipe of ⅜-inch bore.

COMPARISON OF READINGS OF CERTAIN GAS SAMPLERS.

Fig. 70 shows the results of using simultaneously the code "multitubular sampler" at the base of the stack and a single small pipe a few inches above it, reaching across the stack base, and perforated with several small holes at intervals. It will be noticed that the multitubular sampler gave a more even line, on account of its containing a large storage space; the daily average for the two was the same within 0.1 per cent. But this excellent showing with the multitubular sampler was obtained only by constant care of it, for it gave a great deal of trouble from leakage.

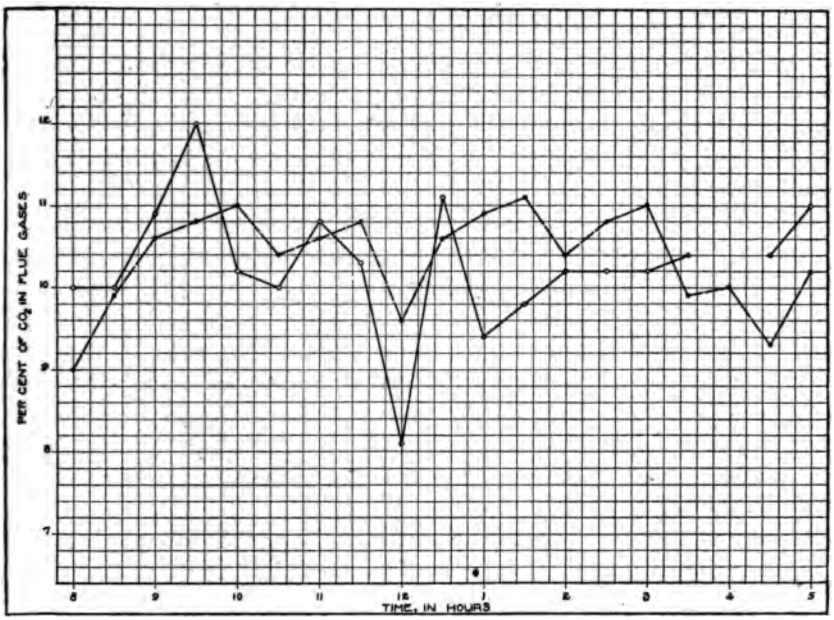


FIG. 70.—Comparison of readings of multitubular gas sampler (broken line) and of single tube in stack (solid line); test 168.

The current of gas through the small sampling tubes is too slow, so that the soot and small particles of ash settle in them and harden, thus gradually stopping the openings. Tubes used in sampling from streams of gas carrying the most soot and ash become stopped sooner than others. Thus the multitubular sampler loses the apparent advantage, which led to its design, of drawing a sample from every portion of cross section of the gas passage, and thereby loses also its value as a flue-gas sampler. It may be stated here that when the sampler was taken out, after two years of usage, about three-fourths of the sampling tubes were found to be stopped up, although the sampler had been often blown out with steam. Its worst disadvantage lay in its leveling all readings considerably, so that the man running the fire could not depend on it for guidance so much as the single-tube sampler. For these reasons the A. S. M. E. multitubular sampler was permanently discarded.

The above-described faults of the multitubular sampler would not be so serious when using coals high in "fixed carbon."

FLUE-GAS SAMPLER.

Fig. 71 shows a design of a different form of flue-gas sampler which has been installed at the fuel-testing plant. The purpose of this design of collector is to obtain gas from various portions of the stack and mix it before its temperature is taken and a sample drawn for analysis. This sampler is built of No. 16 sheet iron, and consists of a cylinder 5 inches in diameter to which are connected, by means of a double cone-shaped body, six scoops making an angle of 45° with the axis of the cylinder. The area of the cross section of these scoops is 2.25 by 3 inches. In the bottom of each of the scoops is an opening which diminishes in width toward the center of the sampler, making the opening proportional at all points to the respective distances of the points from the center. The openings are shown in the bottom view of the sampler (fig. 71). The sampler is placed in the round portion of the stack about 2 feet below the damper, the ends of the scoops being about 4 inches above the top of the hood. The largest diameter across the scoops is about 6 inches smaller than the diameter of the stack.

The sample of gas is drawn through a $\frac{1}{4}$-inch pipe, the end of which is inserted to the center of the 5-inch cylinder, as shown. The bulb of a flue-gas thermometer is also placed at the center of the cylinder near the $\frac{1}{4}$-inch pipe, so that the temperature of the flue gas and the sample of gas for analysis are taken at the same place. It is very probable that by this design of the sampler and location of the thermometer and sampling tube the average temperature and composition of the flue gas are obtained. To prevent the cooling of the gases by radiation after they have left the heating surface of the boiler the base of the stack was covered with asbestos. On close examination at the end of five months' constant use this sampler was found in perfect order in every respect and free from soot, both inside and out.

UNACCOUNTED-FOR PERCENTAGES PROBABLY TOO HIGH.

Of late years the opinion has been gaining ground that all gases increase in specific heat as their temperatures are raised. If this is true, more heat is lost up the flue than has been calculated on the basis that the specific heats of dry flue gases and steam were respectively constant at 0.24 and 0.48 under constant pressure.

If we assume, for instance, that the data given in E. Damour's Industrial Furnaces are correct, at an average flue temperature of 662° F. (350° C.) the true amount of heat lost up the flue was roughly 5 per cent more than the amount regularly calculated—about 1 per cent of the heating value of the fuel. This loss would be subtracted directly from the unaccounted-for heat; for instance, if the latter is given as 15 per cent it may really be about 14 per cent. But in consideration of the fact that in the last few years little work has been

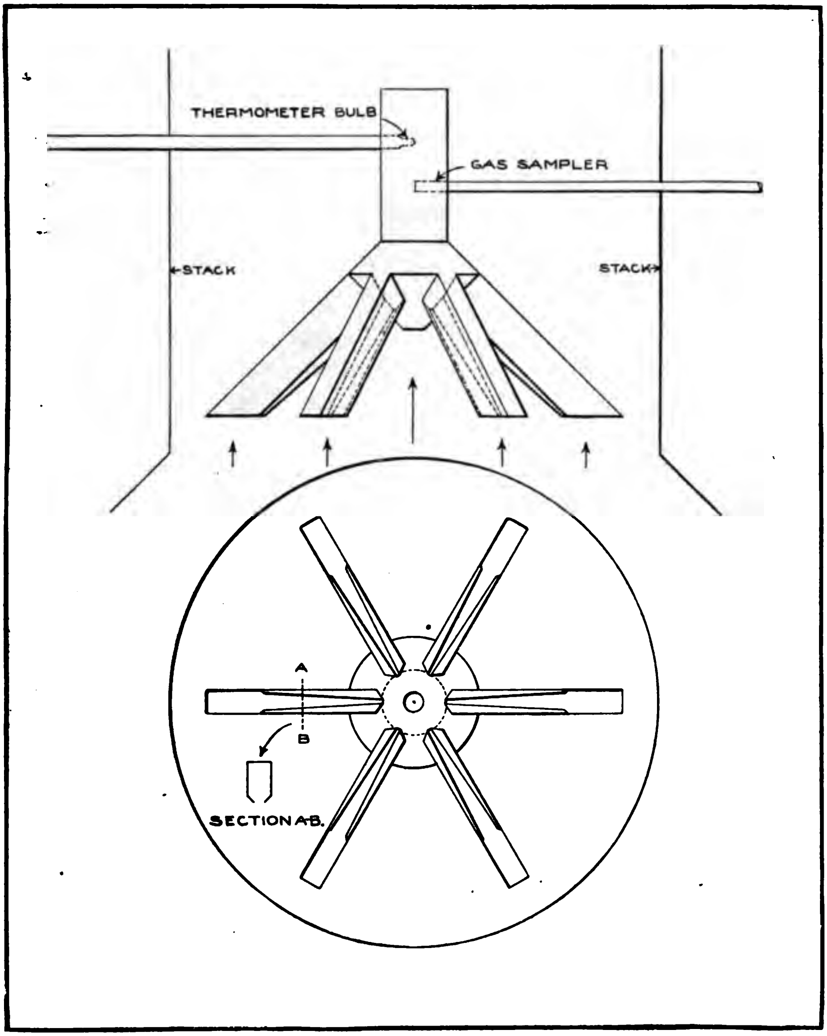


Fig. 71.—Flue-gas sampler installed to replace A. S. M. E. multitubular sampler.

done by physicists on the specific heats of gases at high temperatures the values given by Damour are probably not final, and so the calculations here given are subject to withdrawal.

PROBABILITY CURVES.

It is stated on pages 132 and 146 that when the calculated values of certain "constants" sought for are plotted according to the number of constants falling in each narrow group the free-hand curve drawn through the points resembles a probability curve, and the peak is at a certain value of the constant. This relation makes it probable that the true value of the constant is the peak value, especially if the curve is narrow and symmetrical on the two sides and if the arithmetical average of all the points falls close to the peak of the curve. Perhaps the explanation can be best stated by reference to fig. 72.

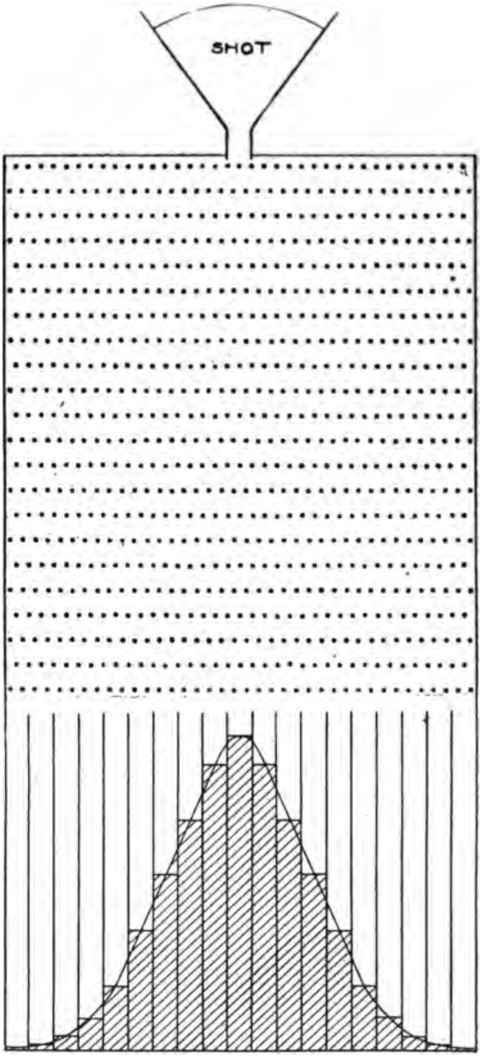


FIG. 72.—Diagram illustrating probability curve.

When shot are dropped into the funnel they ought to fall into a vertical column the width of the funnel, but they will actually spread out, owing to obstructions. The curve drawn through the tops of the piles is a probability curve.

If a man were measuring a length carefully (as with a tape or with a micrometer), while very few of his readings would coincide if a large number of readings were used, the arithmetical average would be closely correct.

If all his readings were sorted according to lengths as read and plotted with the vertical ordinate as the number of readings falling in each group and the horizontal ordinate as the average length of the readings in the groups a curve would result much like a probability curve. But suppose it was questionable whether or not the measured object changed length in unknown ways, if many measurements were taken the width of the curve would give a clew as to whether or not there really was any constant length. If a large number of readings formed a curve close to a theoretical probability curve the presumption of constant length would be nearly justifiable.

Perhaps the best treatment of this subject for engineers is in J. W. Mellor's Higher Mathematics for Students of Chemistry and Physics, a very helpful book to the chemical engineer.

The equation to this curve is

$$y = ke^{-h^2x^2}$$

in which y = height of vertical ordinate at any point.
x = horizontal distance of any point on the curve from the center line passing up and down through the peak.
e = base of hyperbolic system of logarithms, = 2.7183.
h = a constant for each curve, which determines its width; the larger h the narrower the curve, and hence the more reliable as an indicator of the probable value sought.
k = a constant for each curve, determining its height.

The boiler division has plotted a number of curves of this equation, one or another of which is used to fit over any curve to which it bears a strong resemblance. But even if the fit is perfect no more is proved than that there is a strong probability that the figure sought is constant at the peak value. However, even this use of the equation and curves will serve to indicate whether a guess is along the right path, and in this way their use is sure to increase when they are generally known among engineers.

RELATION OF TEMPERATURE OF PRODUCTS OF COMBUSTION TO POUNDS OF AIR USED.

Fig. 73 was prepared as a graphic illustration to show the different comparative temperature elevations attainable by completely burning various fuels, on the assumption that the specific heats of gases at constant pressure do not change with increase of temperature. It was thought that this assumption was wrong, but in the absence of more definite values it was decided to use constants. The general effect of this assumption is probably to make the temperatures with small air excesses too high; thus all the curves are somewhat too steep. In calculating the temperature the specific and latent heat of moisture in fuel and moisture formed by combustion have been considered.

The main object of the chart is to show that some Illinois coals are capable of use in high-temperature work, as in making malleable-iron castings. In fact, by preheating the air used for combustion, Illinois coals are now burned in reverberatory furnaces in Chicago

and St. Louis. The curve shows that lignites could be used with preheating, especially as some lignites are very low in sulphur and burn freely with a long, hot flame.

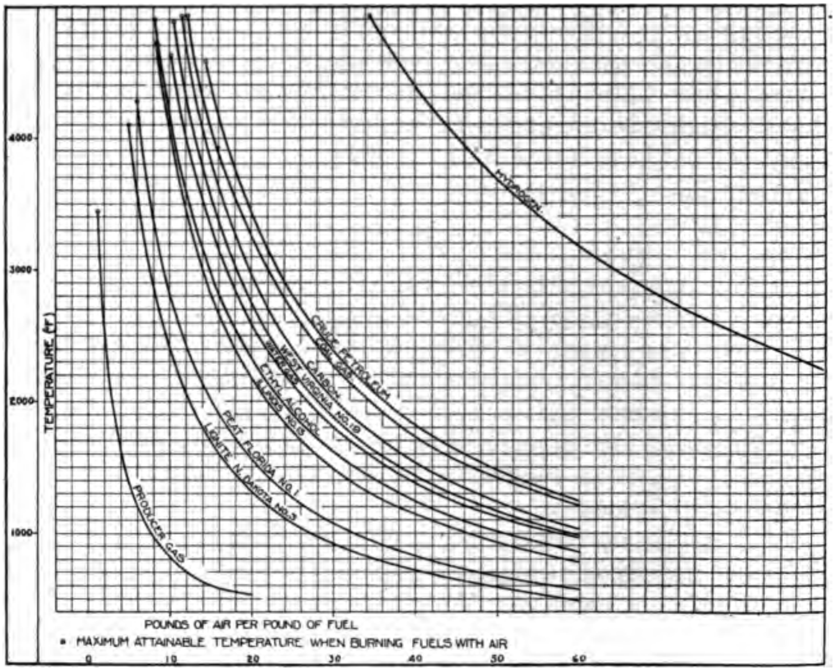


Fig. 73.—Theoretical curves showing relation of temperature of products of combustion to pounds of air used per pound of various fuels.

CIRCULATION INDICATOR.

The construction of the circulation indicator is shown in fig. 74, which is a view of the instrument as mounted in the boiler. There are six essential parts which go to make up the indicator, as follows: The wheel or propeller, the contact strip, the brush that rests on it, the shaft, the supports or bearings of the shaft, and the receiving instrument (which may be a telephone).

The wheel is made up of four copper blades, secured to spokes by copper rivets and set at an angle of 30° with the axis of the shaft. The spokes are attached to a piece of brass tubing that acts as a hub and also as a support for the contact strip.

The contact strip is mounted on an insulating drum consisting of a glass tube about 1½ inches long slipped on the brass hub, which it fits tightly. A strip of copper about one-eighth inch wide and one thirty-second inch thick is bound to the glass tube with copper wire, and is electrically connected to the hub of the wheel by a copper-wire bond.

The brush is a piece of watch spring, supported on a copper bar that is insulated from the remainder of the instrument by mica washers. It is arranged at right angles to the contact strip, with its end resting lightly thereon so as to make and break contact with the copper strip once every revolution of the wheel. A copper wire, that connects to a telephone receiver on the outside of the boiler through a 2-volt battery, is bonded to the brush support and insulated by means of rubber tubing at the point where it passes out of the boiler between the hand-hole cover and the water leg. The other wire from the telephone receiver is grounded to the boiler, as shown. By using a low voltage on the line the current is not short circuited much through the water in the boiler.

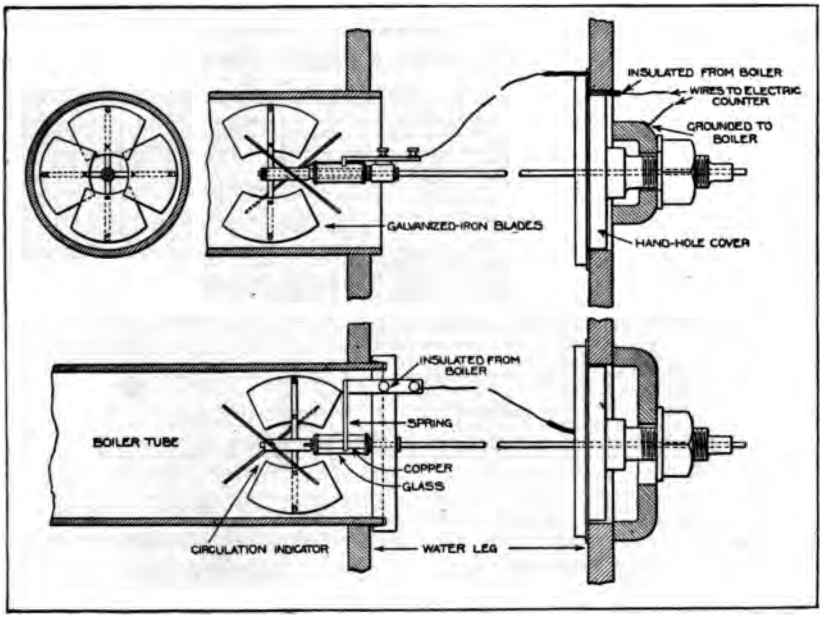


FIG. 74.—Circulation indicator mounted in boiler.

The shaft on which this instrument turns is a piece of brass wire about one-eighth inch in diameter and about 16 inches long. Two collars attached to the shaft close to the wheel, one on each side of the support, serve to keep the shaft from moving back and forth, and one of them, in conjunction with a cotter pin in the end of the shaft, holds the propeller in place.

One support for the shaft, at the end nearest the wheel, is a bar of brass with a hole in the center for the shaft and a slot on each end. These slots, which engage on the outside edge of the boiler tube, as shown, facilitate the centering of the instrument and changing from one tube to another. The other support for the shaft was obtained by drilling a hole through the center of a hand-hole cover and adding a small stuffing box made from the gland of a valve.

In the operation of this instrument the flow of water in any tube of the boiler in which the circulation indicator might be placed causes the wheel to rotate at a rate of speed proportional to the rate of flow. By placing the receiver to the ear a click is heard for each revolution, and one revolution of the indicator means the passage of approximately 1 foot of water. As the speed of rotation in all trials up to date has not been too high for an observer to count the clicks, no difficulty was encountered in keeping a record of the rate of flow in any boiler tube under observation under varying conditions of operation of the boiler.

Several instruments were built and tried before success was attained with this one. The instrument has lately been used to work an automatic counter through a couple of telegraph relays.

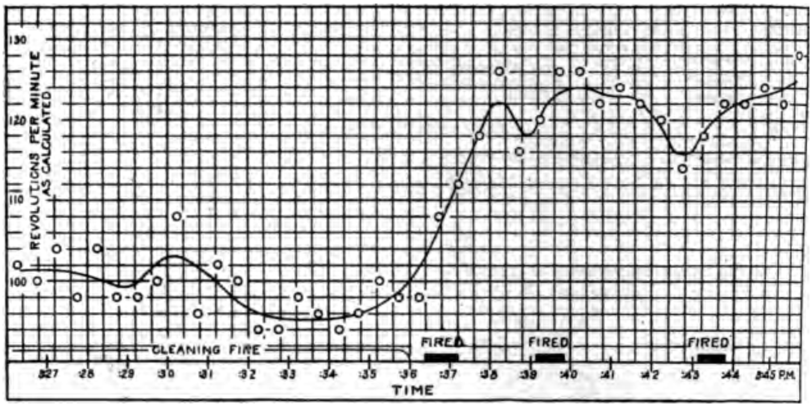


FIG. 75.—Result of observations with circulation counter (propeller in back of boiler, middle tube, third row from bottom); test 379. Revolutions per minute calculated from averages of two readings of revolutions per fifteen seconds.

For information obtained see figs. 7 (p. 16) and 75 and pages 163 and 164.

Fig. 75 shows the effect of cleaning fires, and of firing, on the speed of water circulation in a tube of the boiler, as measured relatively by the circulation indicator illustrated in fig. 74 and described on pages 160–2. The circulation is prompt in its changes and the values obtained vary considerably. The readings were taken by recording the number of revolutions in a fifteen-second interval opposite time figures, and from such data the temporary rate in revolutions per minute was calculated and plotted on this chart.

The curves of fig. 7 (p. 16) are based on readings taken for several days with the circulation indicator. The data from which the two curves were plotted were obtained by counting the total number of revolutions of the indicator for each half-hourly period, and by calculating the percentage of builder's rated horsepower of boiler developed for each such period, respectively. The small circles give the positions of points and the numbers in the large circles near by give the number of half-hours fulfilling the coordinate values of the points. After plotting, the points were averaged in value in both horizontal and vertical strips, each point being included for averaging as many times as indicated by the number in the circle near by. Thus the two curves were determined. It will be noticed that they are very close together, indicating the reliability of the method of working up the data.

The important point is that the circulation rapidly drops behind the amount of steam made (per cent of rated capacity developed), especially at high rates of working. Thus at 70 per cent of rated capacity the average speed of rotation of the indicator was 80 revolutions per minute. At 105 per cent of rated capacity the rate of revolution was 102, whereas to be proportional it should have been 120; the speed of circulation fell about 15 per cent short.

This result is reasonable when we consider that, so far as one can make any speculations, the circulating forces are perhaps roughly proportional to the amount of steam which is generated and entrained with the rising water, whereas the frictional resistance to circulation is perhaps proportional to the square of the average velocity of circulation.

This failure of circulation to keep up proportionally with demands on it must decrease the efficiency of the boiler at higher rates of working, by allowing a proportionally larger percentage of the water-heating surface to be covered with steam bubbles, thus virtually reducing the heating surface. That this condition does supervene is indicated on a number of charts, for instance those shown in figs. 5 (p. 14) and 8 (p. 17), which should be noted in this connection.

At a later date the circulation indicator was put in the middle tube of the lowest row of tubes, this being one of the tubes inclosed in clay tiles except at the rear end. The revolutions per minute for various capacities are given in the following table:

Readings of circulation indicator showing revolutions per minute for various capacities.

	Capacity.			
	58.2.	91.4.	118.2.	92.2.
Number of readings	78	8	7	12
Revolutions per minute	217	257	273	291

The number of revolutions at any capacity is approximately three times as great as the number shown in fig. 7 for the second row of tubes just above.

In an earlier experiment the same circulation indicator was placed in the third row of tubes from the top of the boiler, and it was found that the rate of revolution was very slow indeed. This result indicates that the bottom row of tubes is doing far more work than any other row, and that as we go from the bottom row up the amount of work done decreases very rapidly.

The probability that the bottom row of tubes absorbs so large a portion of the total heat, absorbed mostly on account of conduction through the clay tiles and radiation to the exposed portion of the tubes in the rear over the hot brickwork, makes it easy to realize that the efficiency of the boiler as a heat absorber may well rise far more rapidly with increasing furnace temperature than is indicated by the equation for heat absorption from the gases due to convection only, as developed on pages 129 and 130.

C-SHAPED v. FLAT-BOTTOMED TUBE TILES.

In boilers of the Heine furnace type the bottom row of tubes is incased in clay tiles. Such an installation is advantageous when coals break down, evolving gases difficult to burn, for the clay tiles serve a far better cause in protecting the burning gases from sudden cooling, and in acting as a small heat reservoir, than in protecting the tubes from burning.

The first tiles used by the testing plant were of a C shape inside and out, and although they were made of excellent material they were so easily damaged by fire tools, and cracked so often from sudden temperature changes, that a new set had to be put in every two or three months. Later, both boilers were fitted with tiles which are flat on the bottom, giving the furnace roof the appearance of a ceiling. They are only 15 per cent heavier than the old C tiles, and could easily be made as light as the old tiles by cutting off the upper outside corners, above the tubes. The new tiles have withstood hot fires for over a year and are still good. They are among the most satisfactory parts of the boiler equipment. The difficulty referred to has been experienced at several power houses, and overcome in the same way, with equal satisfaction.

ORSAT TOTALS.

The sum of the percentages of CO_2, O_2, and CO of an Orsat gas analysis is not at all constant. The sum is usually low at the start of a test and gradually rises during the first two hours. It also varies from day to day and from coal to coal. The first explanation suggested was that the available hydrogen of the coal burned to water that condensed before the gas sample arrived at the Orsat measuring tube, so that out of every hundred volumes of air which entered the furnace one or two volumes might well be missing in the

Orsat measuring tube. On this assumption, when the same quantity of air is used to burn various fuels those highest in available hydrogen should give the lowest totals of Orsat analyses. To test this reasoning, a tabulation was made, headed "Classification of average flue-gas totals on basis of per cent of available hydrogen in dry coal." Many tests were grouped, first according to pounds of dry chimney gases per pound of "combustible." The tests of each of these groups were then reclassified according to per cent of available hydrogen in dry coal. For each subgroup the average was found for the Orsat totals of CO_2, O_2, and CO. A glance along the horizontal rows of flue-gas totals shows but little relation between available hydrogen and flue-gas totals. This failure to connect per cent of available hydrogen with shortage in Orsat totals suggests that other causes may be at work.

Perhaps the occurrence of low totals in the first part of a test is due to the fact that an oxygen molecule may combine with carbon and form two CO molecules, which will occupy twice the space, thereby making the Orsat totals higher. During the first part of a test the CO is low, and later it rises. CO and available hydrogen have opposite effects on the totals. So it is, after all, not to be expected that either taken alone will show anything. More work will be done on this problem.

Classification of averqge flue-gas totals on basis of per cent of available hydrogen in dry coal.

	Per cent of available hydrogen in dry coal.									
	Under 3.	3 to 3.2.[a]	[a]3.4 to 3.6.	3.6 to 3.8.	3.8 to 4.0.	4.0 to 4.2.	4.2 to 4.4.	4.4 to 4.6.	4.6 to 4.8.	4.8 to 5.
Less than 18 pounds of dry chimney gases per pound of combustible:										
Number of tests	2	......	......	1	2	8	8	5	3	......
Average per cent of available hydrogen in dry coal.	2.48	......	......	3.66	3.86	4.05	4.29	4.56	4.61	......
Average of flue-gas totals (CO_2+O_2+CO)	19.33	......	......	19.38	18.55	19.16	18.60	19.07	18.69	......
From 18 to 19 pounds of dry chimney gases per pound of combustible:										
Number of tests	......	......	1	2	2	6	11	11	9	......
Average per cent of available hydrogen in dry coal.	......	......	3.42	3.72	3.92	4.08	4.30	4.54	4.67	......
Average of flue-gas totals (CO_2+O_2+CO)	......	......	18.92	18.71	19.15	19.04	18.72	18.82	18.62	......
From 19 to 20 pounds of dry chimney gases per pound of combustible:										
Number of tests	1	......	2	4	7	14	8	5	5	......
Average per cent of available hydrogen in dry coal.	2.31	......	3.50	3.71	3.88	4.07	4.30	4.52	4.68	......
Average of flue-gas totals (CO_2+O_2+CO)	19.16	......	19.25	19.42	19.01	19.07	18.92	19.08	19.08	......
From 20 to 21 pounds of dry chimney gases per pound of combustible:										
Number of tests	2	......	......	3	2	12	11	9	5	......
Average per cent of available hydrogen in dry coal.	2.49	......	......	3.76	3.98	4.08	4.30	4.51	4.72	......
Average of flue-gas totals (CO_2+O_2+CO)	19.87	......	......	18.91	19.79	19.48	19.23	18.89	18.98	......

[a] No fuels in the 3.2 to 3.4 per cent class.

Classification of average flue-gas totals on basis of per cent of available hydrogen in dry coal—Continued.

	Per cent of available hydrogen in dry coal.									
	Under 3.	3 to 3.2.	3.4 to 3.6.	3.6 to 3.8.	3.8 to 4.0.	4.0 to 4.2.	4.2 to 4.4.	4.4 to 4.6.	4.6 to 4.8.	4.8 to 5.
From 21 to 22 pounds of dry chimney gases per pound of combustible:										
Number of tests	......	......	1	3	1	7	8	3	5	......
Average per cent of available hydrogen in dry coal	......	......	3.56	3.70	3.99	4.07	4.27	4.36	4.66	......
Average of flue-gas totals (CO_2+O_2+CO)	......	......	19.29	19.23	19.65	19.52	19.17	19.36	19.08	......
From 22 to 23 pounds of dry chimney gases per pound of combustible:										
Number of tests	......	......	1	3	......	5	3	8	5	1
Average per cent of available hydrogen in dry coal	......	......	3.49	3.69	......	4.06	4.29	4.48	4.69	4.85
Average of flue-gas totals (CO_2+O_2+CO)	......	......	19.10	19.48	......	19.82	19.19	19.17	19.22	19.20
From 23 to 24 pounds of dry chimney gases per pound of combustible:										
Number of tests	......	......	1	......	1	3	5	10	2	......
Average per cent of available hydrogen in dry coal	......	......	3.47	......	3.88	4.04	4.27	4.51	4.68	......
Average of flue-gas totals (CO_2+O_2+CO)	......	......	18.92	......	19.59	20.00	19.58	19.36	19.25	......
24 pounds or more of dry chimney gases per pound of combustible:										
Number of tests	1	1	3	3	2	6	4	7	2	4
Average per cent of available hydrogen in dry coal	2.89	3.17	3.53	3.71	3.98	4.08	4.31	4.52	4.71	4.85
Average of flue-gas totals (CO_2+O_2+CO)	18.91	20.07	19.70	19.67	19.45	19.72	19.45	19.43	18.45	19.39

PER CENT OF CO IN COMBUSTION CHAMBER.

Fig. 14 (p. 23) shows that when combustion-chamber temperatures are high, the per cent of CO in the rear of the combustion chamber is high and the totals of CO_2, O_2, and CO are low. This concurrence of high CO and low totals of Orsat analyses has often been noticed. As a converse test, the classification tabulated below was made on per cent of CO as a basis, to obtain the average of the Orsat totals. They are practically constant until the CO becomes high, when they drop at a comparatively rapid rate. This relation is of the same nature as that indicated in fig. 14 (p. 23). No explanation is given here, as several possible ones were found to be doubtful on investigation.

Classification of Orsat totals on basis of volumetric per cent of CO in combustion chamber (*tests 318–382*).

	Per cent of CO.										
	0 to 0.10.	0.10 to 0.20.	0.20 to 0.30.	0.30 to 0.40.	0.40 to 0.50.	0.50 to 0.60.	0.60 to 0.70.	0.70 to 0.80.	0.80 to 0.90.	0.90 to 1.00	Over 1.00.
Number of readings	82	31	38	18	17	7	9	4	5	2	7
Average of 100—(CO_2+CO+O_2)	18.5	18.4	18.5	18.5	18.5	18.5	18.3	18.9	18.2	15.1	17.4

The following table was constructed to ascertain whether such conditions of poor combustion as permitted a high percentage of CO in the rear of the combustion chamber also conduced to smoke production. The finding is in the affirmative. See also the chart shown in fig. 33 (p. 56), based on per cent of black smoke, in which the per cent of CO rises rapidly with the per cent of smoke.

Classification of smoke production on basis of volumetric per cent of CO in combustion chamber.

	Per cent of CO.							
	0 to 0.10.	0.10 to 0.20.	0.20 to 0.30.	0.30 to 0.40.	0.40 to 0.50.	0.50 to 0.60.	0.60 to 0.90.	0.90 up.
Number of tests	9	8	4	4	4	1	1	1
Average per cent of CO in combustion chamber, volumetric	0.03	0.14	0.23	0.34	0.44	0.58	0.83	1.10
Average per cent of black smoke	13.8	19.9	21.8	18.1	26.3	38.5	40.0	39.0

POUNDS OF DRY CHIMNEY GASES PER POUND OF "COMBUSTIBLE."

The subjoined tabulation of pounds of dry chimney gases per pound of "combustible" is based on intensity of draft under stack damper and difference of draft under stack damper and draft over fire. This table was made to ascertain whether the pounds of air used could be approximated by draft readings. As there was also air leakage, which varied with the amount of draft carried, it seemed best to average out the error by using separate readings for different values of stack draft. However, such a classification seems to be so greatly influenced by rate of combustion and air leakage as to make it of little value. The table shows a small increase of pounds of dry chimney gases per pound of "combustible" as the difference of draft increases.

Classification of dry chimney gases per pound of "combustible" on basis of stack draft and difference of draft under stack damper and draft over fire.

	Stack draft.												
	Under 0.40.	0.40 to 0.425.	0.425 to 0.45.	0.45 to 0.475.	0.475 to 0.50.	0.50 to 0.525.	0.525 to 0.55.	0.55 to 0.575.	0.575 to 0.60.	0.60 to 0.625.	0.625 to 0.65.	0.65 to 0.675.	0.675 up.
Number of tests	18	23	12	25	23	17	14	21	16	28	18	10	32
Average difference of stack draft and draft over fire	0.25	0.29	0.32	0.32	0.34	0.35	0.37	0.38	0.41	0.41	0.44	0.47	0.54
Average pounds of dry chimney gases per pound of combustible	19.75	19.04	18.25	19.79	20.02	19.52	21.09	21.18	22.08	22.16	22.92	21.86	21.91

EFFECT OF DIRECTION, VELOCITY, RELATIVE HUMIDITY, AND TEMPERATURE OF AIR ON EFFICIENCY 72*.

Inasmuch as the boilers stood in a poorly built wooden structure, near two large doors, which were always open in summer and sometimes in winter, it was thought that the cooling of the boiler room by

the bridge wall. The opposite from the relation expected appears in the accompanying table, which shows that the greater the per cent of ash carried away the less the unaccounted-for loss—that a high percentage loss of ash does not mean a high unaccounted-for loss. As the average difference of draft under stack damper and draft over fire increases the ash lost over the bridge wall increases, as might be expected.

The following is offered as an explanation of the table: With higher draft there is an increased rate of combustion; the temperature of combustion is increased; the pounds of dry chimney gases per pound of "combustible" are decreased; a higher initial temperature and increased rate of combustion will give a higher stack temperature, and this increased temperature will increase the loss up the stack and subtract almost directly from the unaccounted-for loss; and with increased rate of combustion the per cent of radiation loss for each pound of coal burned will be less and this reduction will enter directly into the unaccounted-for loss. These factors tend to decrease the unaccounted-for loss. On the other hand, with higher rate of combustion and higher temperatures the gases are carried through the furnace faster and there is a greater amount of incomplete combustion owing to the fact that less time is taken in passing through the furnace. Moreover, as there is less excess of air and a higher temperature, the unaccounted-for loss will directly increase because hydrocarbon losses are not determined. There is necessarily a balancing of these losses and gains. The table shows their average effect only.

Three classifications showing relation between "unaccounted-for" loss and ash passing over bridge wall.

Per cent of ash lost over bridge wall, referred to combustible burned	....	0.58	1.24	1.73	2.26	2.69	3.26	3.72	4.42	7.01
Number of tests	....	24	26	30	28	19	18	20	25	19
Average per cent of unaccounted-for loss from heat balance	....	9.83	11.74	11.23	11.24	9.73	9.40	10.49	9.52	8.45
Average difference of draft under stack damper and draft over fire, inch of water	....	0.35	0.35	0.34	0.36	0.38	0.37	0.37	0.39	0.43
Average per cent of ash lost over bridge wall	0.27	0.79	1.24	1.78	2.25	2.80	3.20	3.72	4.56	5.90
Number of tests	13	26	34	29	33	20	23	14	10	9
Average per cent of unaccounted-for loss from heat balance	10.01	10.55	12.12	10.78	10.44	9.53	9.68	9.46	7.99	9.01
Average per cent of unaccounted-for loss	5.69	7.59	8.54	9.48	10.48	11.45	12.55	13.38	14.51	16.70
Number of tests	26	24	22	29	20	30	22	12	11	15
Per cent of ash lost over bridge wall, referred to combustible burned	3.81	2.80	3.10	2.64	2.51	2.88	2.83	2.81	1.75	2.16
Average per cent of ash lost over bridge wall	3.04	2.24	2.45	2.10	1.99	2.26	2.21	2.19	1.44	1.75

winds might have some appreciable tendency to lower the efficiency 72*.

With the data from about 305 tests, the problem was attacked in several ways, as given below:

1. The winds were classified in four groups,—(*a*) from the north and northeast, (*b*) from the east and southeast, (*c*) from the south and southwest, (*d*) from the west and northwest—and then all tests were classified according to the prevailing direction of the wind for that day, and the individual tests falling in each of the four wind groups were plotted by means of the two ordinates, efficiency 72* and velocity of wind in miles per hour. It was found that there was no appreciable effect on efficiency due to wind velocity. In the above-mentioned subdivisions the tests of all groups (*a*, *b*, *c*, and *d*) were arranged in subgroups according to the outside air temperatures—for instance, the tests falling under wind from the east and southeast were divided into three subgroups, in which the ranges of outside air temperature were "below 40° F.," "40° to 50° F.," and "50° to 60° F."

2. With the same four groups of wind directions (*a*, *b*, *c*, and *d*) the item 72* (so-called "boiler efficiency") was plotted in each group with the items: (*e*) velocity of wind in miles per hour, (*f*) relative humidity of outside atmosphere, (*g*) outside air temperature, and (*h*) average diameter of coal. In group 2 (*e*) the velocity of wind again had no noticeable effect. For all directions of wind excepting from the north and northeast, high relative humidity (*f*) of the outside atmosphere appeared to lower the efficiency somewhat. A rise of outside-air temperature (*g*) appeared to cause a slight rise in efficiency, but not any more than results from an equal reduction in stack temperature, so that the effect on radiation is not noticeable. The outside doors were generally closed in winter, however. The average diameter of the coal (*h*) varied only slightly, and it apparently had no influence in disguising any of the other curves (*e*, *f*, and *g*).

The general conclusion is that calculations of radiation are not likely to be appreciably in error owing to changes in weather conditions, unless it is substantiated on further investigation that the relative humidity influences the amount of heat lost by convection or else retards the combustion of coal. Efficiency 72* was used because the "unaccounted-for" item is not reliable.

RELATION OF UNACCOUNTED-FOR LOSS TO ASH PASSING OVER BRIDGE WALL.

It was thought that possibly all the coal which was blown up from the fuel bed and carried away with the gases did not burn, and that a clew to incomplete combustion might be obtained by comparing the unaccounted-for items of the heat balance with the ash lost over the bridge wall. The opposite from the relation expected appears in the accompanying table, which shows that the greater the per cent of ash carried away the less the unaccounted-for loss—that a high percentage loss of ash does not mean a high unaccounted-for loss. As the average difference of draft under stack damper and draft over fire increases the ash lost over the bridge wall increases, as might be expected.

The following is offered as an explanation of the table: With higher draft there is an increased rate of combustion; the temperature of combustion is increased; the pounds of dry chimney gases per pound of "combustible" are decreased; a higher initial temperature and increased rate of combustion will give a higher stack temperature, and this increased temperature will increase the loss up the stack and subtract almost directly from the unaccounted-for loss; and with increased rate of combustion the per cent of radiation loss for each pound of coal burned will be less and this reduction will enter directly into the unaccounted-for loss. These factors tend to decrease the unaccounted-for loss. On the other hand, with higher rate of combustion and higher temperatures the gases are carried through the furnace faster and there is a greater amount of incomplete combustion owing to the fact that less time is taken in passing through the furnace. Moreover, as there is less excess of air and a higher temperature, the unaccounted-for loss will directly increase because hydrocarbon losses are not determined. There is necessarily a balancing of these losses and gains. The table shows their average effect only.

Three classifications showing relation between "unaccounted-for" loss and ash passing over bridge wall.

Per cent of ash lost over bridge wall, referred to combustible burned	....	0.58	1.24	1.73	2.26	2.69	3.26	3.72	4.42	7.01
Number of tests	....	24	26	30	28	19	18	20	25	19
Average per cent of unaccounted-for loss from heat balance	....	9.83	11.74	11.23	11.24	9.73	9.40	10.49	9.52	8.45
Average difference of draft under stack damper and draft over fire, inch of water	....	0.35	0.35	0.34	0.36	0.38	0.37	0.37	0.39	0.43
Average per cent of ash lost over bridge wall	0.27	0.79	1.24	1.78	2.25	2.80	3.20	3.72	4.56	5.90
Number of tests	13	26	34	29	33	20	23	14	10	9
Average per cent of unaccounted-for loss from heat balance	10.01	10.55	12.12	10.78	10.44	9.53	9.68	9.46	7.99	9.01
Average per cent of unaccounted-for loss	5.69	7.59	8.54	9.48	10.48	11.45	12.55	13.38	14.51	16.70
Number of tests	26	24	22	29	20	30	22	12	11	15
Per cent of ash lost over bridge wall, referred to combustible burned	3.81	2.80	3.10	2.64	2.51	2.88	2.83	2.81	1.75	2.16
Average per cent of ash lost over bridge wall	3.04	2.24	2.45	2.10	1.99	2.26	2.21	2.19	1.44	1.75

THE LAW OF MASS ACTION.

Although not yet very old, the law of mass action is already one of the most firmly established and useful of the laws of physical chemistry. Its operation is a matter of daily intuition in other fields; e. g., the more water one uses the easier it is to dissolve sugar, salt, etc. But only recently has the law been mathematically formulated in chemistry, and even yet it is often so hard to learn what the reactions are that one does not know which mass-action formula to use; still, the path of some reactions has been determined by finding what formula fitted the observed facts.

To take the simple case of combustion of carbon, it is an observation as old as the art of boiler practice that considerable excess of air is needed above the theoretical amount. Mathematically the situation is as follows:

As soon as some of the oxygen of the air has united with carbon or CO it is no longer available for oxidation of the remaining combustible; worse yet, the molecules formed are in the way, so that the combinations become less and less frequent. All this, of course, is on the supposition that the temperature is kept constant, so as to eliminate other variables. Now, as the above reaction proceeds the masses of oxygen and carbon, as compared with the total masses present, become less and less, whence the name, mass action; they soon become nearly zero.

The above illustration is faulty in one respect—it does not say in what terms the masses are to be measured. Elementary chemistry states that CO and O, for example, combine in just one proportion—28 parts by weight of CO (its molecular weight) and 16 parts by weight of O (its atomic weight). The molecular weight of the oxygen is not taken (it is 32, as there are ordinarily two atoms in a molecule) as the combining weight, because the molecule must first divide. Thus we should really consider 2 molecules of CO and 1 of O_2. For these reasons both combining substances must be considered according to the numbers of gram molecules present—that is, the number of grams of each present divided by its respective molecular weight. Luckily this trouble disappears when working with gases analyzed volumetrically, as with an Orsat apparatus, because the volumetric weights of gases are directly proportional to their molecular weights, as all gases at the same temperature and pressure contain the same number of molecules per unit volume. Even dissociation, either of molecules of H_2O and CO_2 or of molecules of H_2 and O_2 and N_2 into 2H, 2O, and 2N, would not trouble us, because volumes would increase proportionately. All we need to do is to substitute the volumetric percentages of O_2 and of CO or CH_4, for example, of the analysis in the equation corresponding to the particular reaction and obtain the relative indication of the rate of combustion, assuming, of course, the same temperature and pressure in every case.

Example: An analysis of gas from the rear of a combustion chamber through a small opening in a water-jacketed gas sampler showed the two following results, the combustion-chamber temperature in each case being 2,600° F.: (1) O_2, 4 per cent; CO, 0.5 per cent. (2) O_2, 7 per cent; CO, 0.4 per cent. The rest of the volume consisted of nitrogen, water vapor, carbon dioxide, and other gases foreign to this calculation. If the formula of the reaction is $2CO + O_2 \rightleftharpoons 2CO_2$,[a] and if at 2,600° F. the dissociation of CO_2 is only about 0.01 per cent, we may say with very close accuracy that the reaction is not a balanced one, but proceeds to a finish. It can be then written $2CO + O_2 = 2CO_2$.

If the rate of disappearance of CO in the gas is given by $\frac{dx}{dt} = -\text{const.} (CO)^2(O_2)$, the rates of burning CO in the two cases given are (1) $4 \times (0.5)^2 = 1.00$; (2) $7 \times (0.4)^2 = 1.12$.

Thus the net velocity of combustion in the second case is considerably greater—with more oxygen. It would take an almost impossible rise in the CO percentage in the second case to neutralize the effect of 75 per cent more free oxygen. In such calculations care must be taken to include the volume of the steam gas present in the 100 per cent total (not the 100 per cent total of the Orsat analysis). This volume can be roughly calculated, and is considerable in percentage and very variable.

It must be constantly borne in mind that calculations of velocity reactions based on the laws of mass action are liable to be seriously in error owing to disturbing side reactions, catalysis, etc.; but probably less is to be feared here with simple gases at high temperatures than with more complex substances at ordinary temperatures. At any rate, these laws of mass-action are a very valuable guide in such problems, and if the facts do not fit proved formulas well we have applied too little theory; some refining corollaries must be added.

On page 61 is given a calculation based on actual data obtained, and the conclusion is reached that the velocity of combustion decreases enormously from the surface of the fire to the rear of the combustion chamber, where it is relatively very small; the practical application is that little is to be gained by adding further length of smooth combustion chamber, which would be commercially as poor an investment of capital as to add to the length of a Corliss engine cylinder and stroke; we must resort to thorough mixing.

---

[a] The sign $\rightleftharpoons$ indicates that a chemical reaction and a reversing decomposition are going on side by side. The composition of the mixture changes according as combination or dissociation is the more rapid.

The question may arise, How are we to treat cases in which more than one combustible gas is present? Simply by adding the two effects together, as when we say that the pressure of a mixture of gases on the walls of a containing vessel is the sum of the pressures of the constituent gases; the two reactions go on independently side by side. Care must be taken not to add these velocity products without having first multiplied each by its proper reduction factor, which for most substances is imperfectly known at present for high temperatures. For the present, therefore, it is not feasible to get an expression for the comparative total velocities of combustion of all constituents taken together at several points along the flame.

Fig. 31 (p. 51) presents an excellent illustration of decrease of completeness of combustion because of decreasing oxygen mass action.

"Furnace efficiency" should more correctly be called "per cent of completeness of combustion," inasmuch as furnaces are usually fixed in size and shape, and so exert about the same mixing effect in all cases.

In the commercial combustion of fuels, where speed of coal consumption is important, so as to get high capacity, the operator must determine whether he will be most benefited by high temperatures or by a close approach to perfection of combustion. If he must put the heat into material at a high temperature, as in melting pig iron or clinkering cement, he must cut down the air supply even at the cost of a large fall in completeness of combustion due to decreased oxygen mass action, so as to have the temperature of the gases as far as possible above that of the material to be worked. If the temperature of his material is low, as is the water in a boiler, it will not make much difference how much air he uses so far as heat absorption is concerned, within reasonable limits; and larger porportions of air mean larger oxygen mass action and more complete combustion. As a general rule the air supply per pound of fuel must be decreased, at a sacrifice of completeness of combustion, when the temperature of the material into which heat is to be put is high.

The only method of alleviating this condition is by making combustion chambers longer, or, much better yet, by putting some firebrick mixing structure in the path of the gases. As such a structure is damaged more by high than by low temperatures, it should be placed in the first part of the path of the gases to be mixed.

The most economical burning of various fuels for various purposes is largely dependent on proper adjustment of oxygen mass action, assisted by good stream-mixing structures.

DIMENSIONS OF BOILERS AND SETTINGS.

The following is a statement of the dimensions of the boilers and settings at the fuel-testing plant:

Dimensions of Heine water-tube boilers and settings used in steaming tests.

Length of drum	feet	$21\frac{7}{12}$
Inside diameter of drum	inches	42
Number of tubes		116
Internal diameter of tubes	inches	3.26
Outside diameter of tubes	do	3.5
Length of tubes exposed	feet	$17\frac{7}{12}$
Plain grate:		
Width of furnace	do	6.16
Length of furnace	do	6.58
Mean height of furnace	inches	26
Air space	per cent	45
Area of grate surface	square feet	40.55
Rocking grate:		
Width of furnace	feet	6
Length of furnace	do	6.07
Area of grate surface	square feet	36.4
Depth of ash pit below grate	inches	25
Height of stack above grate	feet	113.25
Diameter of stack	inches	37.5
Area of gas passages:		
Stack	square inches	1,104
Draft passage over bridge wall	do	888
Aggregate between lower entrance tubes to boiler	do	1,070
Aggregate between tubes in boiler	do	1,612
Aggregate between upper tubes from boiler	do	640
Area of water-heating surface:		
Tubes	square feet	1,897
Water legs	do	91
Shell	do	43
Total	do	2,031
Superheating area		None.
Total water space	cubic feet	287
Steam space	do	73
Ratio of heating surface to grate surface		50.1 to 1
Ratio of smallest draft area to grate area		1 to 9.1

The boilers were erected by the Heine Boiler Company, and were similar to those in commercial use.[a] When the water stood at 3 inches in the gage glass, boiler No. 1 contained 16,850 pounds of water, and boiler No. 2, 16,755 pounds of water, at 75° F. Each inch of water, as shown by the glass, represented 340 pounds in the boiler. This figure was determined by calibrating the boilers with cold water at about 75° F., by noting the height of water in the gage glass as the water was drawn from the blow-off and weighed.

---

[a] For further description of apparatus see Prof. Paper U. S. Geol. Survey No. 48, 1906, pp. 302-314.

TRUE BOILER EFFICIENCY.

In confirmation of the ideas on boiler efficiency and heat absorption advanced in this study, and of the probability of being able so to construct boilers as to evaporate several times as much water per unit of heating surface, the boiler division has recently begun some accurate experiments on heat transmission through the tubes of small multitubular boilers and finds that the results answer to Professor Perry's theory very closely.

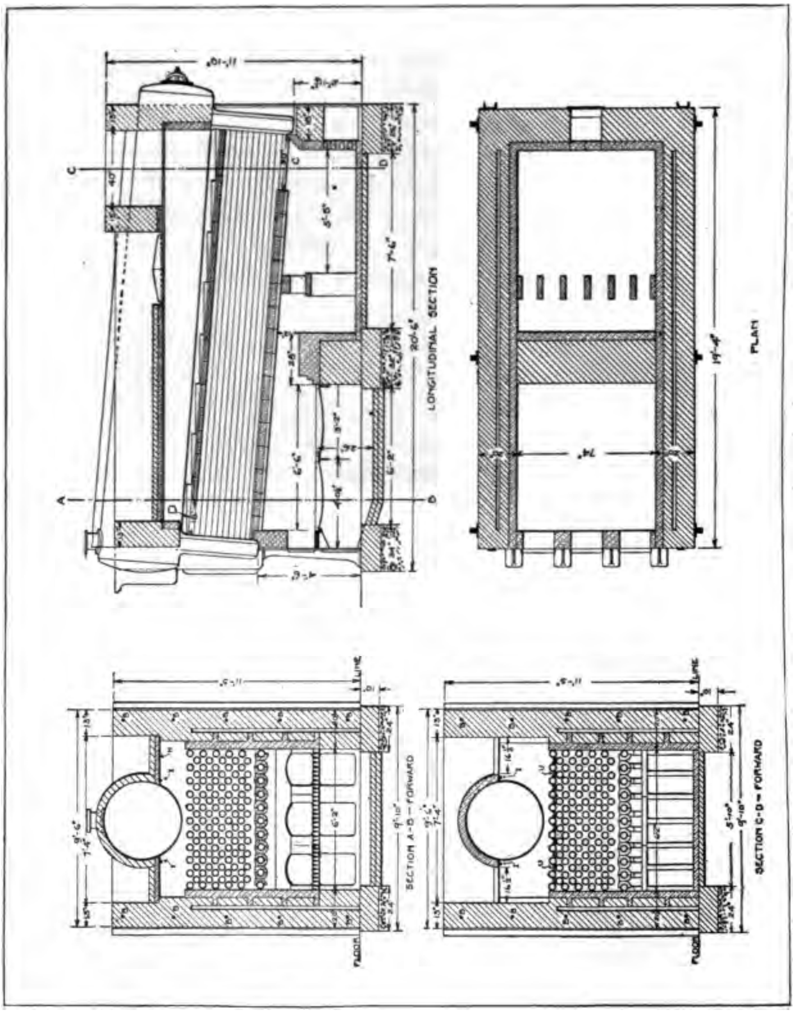


FIG. 76.—Dimensions and details of boiler setting.

An account of the first few experiments will be found in a paper read by Prof. L. P. Breckenridge before the Western Society of Engineers, Chicago, March 20, 1907.

GENERAL CONCLUSIONS.

All the tests that are discussed in this bulletin were made under a Heine boiler with a hand-fired furnace. The principal object of these tests was to determine the relative value of coals for steaming purposes. With this in view each coal was burned to its best advantage for hand firing.

All the tests were made at about the rated capacity of the boiler, carrying a steam pressure of about 80 pounds. The average length of a test was about ten hours. The only variable conditions were thickness of fire and intensity of draft.

While the average efficiencies are fairly high, better efficiency could be obtained with furnaces and other conditions more especially adapted to particular coals. The average efficiency obtained at the fuel-testing plant is about 10 per cent higher than is obtained in good commercial plants. This is true for all coals.

The efficiency used as a basis for comparison of coal tests under a boiler is code item 72*. This is the ratio of the heat carried away in the steam to the calorific value of the "combustible." In determining the amount of "combustible" burned it was considered that the coal which fell through the grate was never fired. This efficiency 72* is the product of boiler and furnace efficiencies.

Per cent of completeness of combustion is the ratio of heat evolved in the furnace to the potential heat in the coal ascending from the grate.

The efficiency of the boiler proper is the ratio of the heat absorbed by the boiler to the heat evolved in the furnace. Efficiency 72* is not commonly subdivided into furnace and boiler efficiency on account of the difficulty of determining the actual heat evolved in the furnace.

The true boiler efficiency is the ratio of the heat absorbed by the boiler to the heat available for absorption. This is the true measure of the ability of a boiler to absorb heat.

Inasmuch as efficiency 72* is the product of furnace and boiler efficiency, it increases with an increase of furnace efficiency, which means that efficiency 72* is higher with coals which are more easily and completely burned. Except in extreme cases it is very little affected by the temperature of combustion. High CO_2 content in the gas analysis is not a definite indication of high efficiency, although some high 72* efficiencies were obtained with high CO_2 content in the gas. The best efficiencies of tests recorded in this paper were obtained with about 10 per cent of CO_2. High CO is always an indication of low 72* efficiency. It does not by itself account for all of the incomplete combustion, but merely indicates poor conditions in the furnace. The other combustible gases which probably pass up the stack, though occurring in very small quantities, will account for heat loss many times as great as the CO loss.

The true boiler efficiency (E_4) is not of constant value in commercial boilers, but varies somewhat with temperature of combustion and capacity. This variation with temperature is due to the heat absorbed by radiation from the fire and the hot brick walls. To increase capacity there must be a proportionate increase in temperature difference between the first layer of water and the film of gas adhering to the tube. Since the temperature of the water is in most cases constant, the temperature of the adhering film of gases will be raised and the flue gases will leave the boiler at a higher temperature.

In general the efficiency is affected by the formation of soot and scale on the heating surface and by defective circulation of water in the boiler. These conditions cause poor absorption of heat and higher flue-gas temperature.

The rate of combustion is affected by the chemical composition of the coal, the size of the coal, the intensity of the draft, and to some extent by the thickness of the fire and the formation of clinker. Bituminous coals high in "volatile matter" burn more quickly than those high in "fixed carbon." Coals ranging in size from one-fourth inch to 1½ inches burn much more rapidly than either very small or very large sizes. This is undoubtedly due to a better distribution of air with these sizes. Fine coal, the formation of clinker, and thick fires hinder the passage of air and reduce the rate of combustion. By increasing the draft, more air is drawn through the fuel bed, causing the coal to burn more rapidly.

With higher rates of combustion less air is used per pound of combustible, the temperature of combustion rises, the gases pass through the boiler faster, and after a certain rate of combustion is reached black smoke is produced. Capacity varies almost directly with the rate of combustion. Extremely high or low rates of combustion reduce efficiency.

The presence of ash in dry coal up to about 15 per cent has very little effect on efficiency and capacity. Above this percentage, however, the efficiency drops.

Moisture reduces efficiency and capacity, perhaps, by hindering combustion.

The presence of sulphur in coal is not detrimental to the value of coal as fuel for steaming purposes except where it exists in certain combinations with other constituents of the ash so as to form fusible clinker which may adhere to the grate.

If there are no other reasons for washing coal than for efficient burning, coal need not be washed, as the efficiency of the furnace and boiler are not increased by washing except with coals of high ash or considerable free pyrites. Washed coal can usually be burned at a higher rate of combustion. The washing of coal does *not decrease the* per cent of black smoke produced.

Most coals when briquetted can be burned at a higher rate of combustion. As a rule briquetted coals burn with little or no smoke.

Bituminous coal should be fired in small quantities every three or four minutes. It is best to fire only on one-half of the grate area at a time. When burning bituminous coal, up to a medium rate of combustion, the production of smoke may be entirely avoided by leaving the furnace doors partly open for a short time immediately after firing. The best thickness of fire ranges from 5 to 10 inches, varying with the intensity of draft of 0.5 to 0.7 inch under the stack damper.

Most of the eastern semibituminous coals, especially the small sizes, cake badly in the fire. When using these coals the fire must be raked frequently. Coal of this class can be fired every five or six minutes and more can be fired at a time than of bituminous coal. Either the spreading or alternate method of firing may be used. Owing to its tendency to crumble, coal of this class usually reaches the boiler room as fine as slack, which reduces its value as a steaming coal. It can be improved for steaming purposes by briquetting.

Good results can be obtained with lignites if a difference of draft of 1½ to 2 inches of water is carried between the ash pit and the stack. With this draft these fuels may be fired in large quantities every six or eight minutes, the spreading method of firing being used. Rocking grates may be used to good advantage in burning lignites.

For hand firing a furnace with a tile roof and large combustion chamber containing good mixing structures is well adapted for burning bituminous and lignitic coals. The mixing structures cause resistance to the passage of furnace gases, and consequently a higher stack draft must be carried to maintain capacity.

COMMERCIAL CONSIDERATIONS.

General.—Inasmuch as the boiler plant is at present the expensive portion of a steaming outfit, and as it probably is possible to cut its cost down to a fraction of the present cost and at the same time obtain a higher efficiency, it is felt that there is good ground for anticipating an enormous improvement in the production of steam power within the next few years. If so, it will not be the first time that a new arrival in a field has spurred on older forms of enterprise to a higher prosperity than they ever dreamed of before. The competition of the gas engine may be the best thing that ever happened to steam engines and turbines.

The statements, theories, and proposals made in this study are widely scattered and may not have been plain because they are mathematically involved. For this reason a short summary will be made here of the possibility of so improving the system of working steam-turbine plants that they may be permanently kept above commercial competition from gas-producer and engine plants in large powers. Of course there is little doubt that a great field immediately awaits the gas engine in smaller plants, say under 5,000 horsepower. All these suggestions are tentative only.

Boilers.—The authors see no reason why boilers can not be constructed, and probably operated with entire satisfaction, which will produce about ten times the amount of steam now obtained per square foot of heating surface, and with no difficulty in obtaining dry steam. The efficiency from coal to steam should easily be made considerably higher than that of a good performance of to-day. Such a plant would require only a fraction of the present investment in steam plants, buildings, and real estate. Perry states in his book, The Steam Engine and Gas and Oil Engines, that he thinks boilers should be made to do ten and possibly twenty times the work they do at present.

Furnaces.—It will probably be found on attempting this reduction of dimensions and cost that the limit will be not in the boiler as such, but in the combustion chamber. Burning a large amount of coal on a small grate area is largely a question of draft and continual riddance of ash, but the rate of travel of gases through a combustion chamber is dependent, practically, only on the amount of carbon burned per unit of time, the rate being about the same no matter what the air supply per pound of carbon. As combustion chambers are now constructed for western coals they are too small, but "small" is a word not to be understood in this connection as referring to volume or length alone. By a "small combustion chamber" is meant a chamber in which either the time spent by the gas in traveling from the front to the rear of the boiler is short or the mixing devices are inefficient or absent. In the discussion of mass action it was stated that mere length of combustion chamber counts for little—that mixing is what counts—and thus there is a possibility of enormously increasing the efficiency of a combustion chamber as a burner of volatile matter. Effort in completing a steam-generating outfit of small dimensions must be largely concerned with the construction of a combustion chamber containing many gas-mixing appliances.

Turbines.—The work on turbines is provisional only, but it is believed that all the assumptions made are on the side of safety; that is, that the over-all efficiency of the turbines working with high superheat and low pressure would probably be greater than estimated.

BIBLIOGRAPHY.

Barr, William M. Combustion of coal and the prevention of smoke. The Norman W. Henley Publishing Company, New York.

A practical catechism for engineers.

Barrus, George H. Boiler tests. D. Van Nostrand, New York.

Booth, William H., and Kershaw, John B. C. Smoke prevention and fuel economy. The Norman W. Henley Publishing Company, New York.

Damour, E. Industrial furnaces and methods of control. Translated by A. L. Quereau, 1906. Eng. and Min. Jour.

Duhem, P. Thermodynamics and chemistry. Translated by George K. Burgess.

Should receive careful study by the chemical engineer.

Hoff, Dr. J. H. van't. Lectures on theoretical and physical chemistry. Translated by Dr. R. A. Lehfeldt. Part 1, chemical dynamics; part 2, chemical statics. Edward Arnold, 37 Bedford street, Strand, London.

Jones, Harry C. Elements of physical chemistry. Macmillan Company.

Kent, William. Steam boiler economy. John Wiley & Sons, New York.

Kershaw, John B. C., and Booth, William H. Smoke prevention and fuel economy. The Norman W. Henley Publishing Company.

Mellor, J. W. Chemical statics and dynamics. Longmans, Green & Co., New York, 1904.

Mellor, J. W. Higher mathematics for students of physics and chemistry. Longmans, Green & Co.

An exceedingly helpful book to engineers, but very poorly indexed. Deserves much deep study by applied scientists.

Meyer, Dr. Oskar Emil. The kinetic theory of gases. Translated by Robert E. Baynes, M. A. Longmans, Green & Co.

A simple and clearly written book on an intricate subject, by an authority. Should be carefully studied by every engineer who deals with gases in any way.

Nernst, Dr. Walther. Theoretical chemistry from the standpoint of Avogadro's rule and thermodynamics. Translated from fourth German edition. Macmillan Company.

Nernst, W., and Wartenberg, H. v. Die Dissociation von Wasserdampf. Zeitsch. f. prakt. Chemie, vol. 56, No. 5, 1906.

Nernst, W., and Wartenberg, H. v. Ueber die Dissociation der Kohlensäure. Zeitsch. f. prakt. Chemie, vol. 56, No. 5, 1906.

Parr, S. W. The classification of coals. Jour. Am. Chem. Soc., vol. 28, No. 10, 1906.

Parsons, H. de B. Steam boilers, their theory and design. A. C. McClurg & Co., Chicago.

Pennsylvania Railroad Company. Locomotive tests and exhibits of Pennsylvania Railroad system at Louisiana Purchase Exposition, St. Louis, 1904. Published by the company, Philadelphia, Pa.

Perry, John. The steam engine and gas and oil engines. Macmillan Company, 1902.

A splendid book; chapters 26, 30, and 33, concerning boilers, are especially good; gist of most matter on true boiler efficiency in footnote of page 591.

Rowan, F. J. The practical physics of the modern steam boiler. A. C. McClurg & Co., Chicago.

Smith, Robert H. Commercial economy in steam and other thermal power plants. J. B. Lippincott Company, Philadelphia, Pa.

Van Deventer, Dr. Charles M. Physical chemistry for beginners. Translated by Dr. R. A. Lehfeldt. Edward Arnold, 37 Bedford street, Strand, London.

Walker, James. Introduction to physical chemistry. Macmillan Company.

Wartenberg, H. v., and Nernst, W. Die Dissociation von Wasserdampf. Zeitsch. f. prakt. Chemie, vol. 56, No. 5, 1906.

Wartenberg, H. v., and Nernst, W. Ueber die Dissociation der Kohlensäure. Zeitsch. f. prakt. *Chemie*, vol. 56, No. 5, 1906.

GLOSSARY.

Absolute temperature. The temperature of a substance reckoned from that temperature—461° below the zero on the Fahrenheit scale and 273° below the zero on the centigrade scale—at which all heat is supposedly absent.

Air-dried coal. A term applied to coal that has been prepared for chemical analysis. The coal is dried at a temperature somewhat above that of the room in which it is to be analyzed, in the atmospheric conditions prevailing in the room, so that the sample will not vary in weight while being handled. No coal has a constant air-drying loss, since its loss in weight varies according to conditions, such as size of coal analyzed, air currents, and weather conditions. Air-drying results are of value only to the chemist who figures them back to coal as received and to dry coal.

Available heat. The portion of the heat supplied to the boiler over and above the amount required to raise the gases from atmospheric to steam temperature.

Available hydrogen. The excess of hydrogen in coal over and above that which is required to unite completely with the oxygen in the coal to form water (H_2O). It is found by subtracting one-eighth of the total oxygen from the total hydrogen.

Avogadro's law. The temperature and pressure being the same, the number of molecules in a unit volume is the same for all gases.

Baffle. A term applied to partitions designed to change the course of moving gases in the combustion chamber or among the boiler tubes.

Base values. A term used to designate the abscissa value of any point on a curve—that is, the horizontal distance of that point from the left side of the chart.

Black body. A term used to designate a hollow body whose walls are all at the same temperature. If an extremely small hole were made in such a body, heat would be radiated through the hole in proportion to the difference of the fourth powers of the absolute temperatures of the black body and the surrounding objects.

Boltzmann and Stefan's law. *See* Stefan and Boltzmann's law.

British thermal unit. That quantity of heat which is required to raise the temperature of 1 pound of pure water through 1° F. at or near 39.1° F., the temperature of maximum density of water. The abbreviation B. t. u. is used in this volume.

Caking coal. A term applied to coal which fuses together when burning—a coal that is not free burning.

Capacity. A term rather loosely used to denote the percentage of steam made, taking as the basis (100 per cent) the rated evaporation designated by the boiler builder.

Carbon—available-hydrogen ratio. The total carbon content of coal divided by the available hydrogen (q. v.).

Carbon, fixed. *See* Fixed carbon.

Carbon—hydrogen ratio of dry coal. The total carbon content divided by the total hydrogen content.

Carbon—hydrogen ratio of coal "as fired," or "as received" (moist coal). The total carbon content divided by the total hydrogen content, including the hydrogen of the free moisture present.

Catalyzer. A substance whose presence, among the substances participating in a chemical reaction, hastens or retards the speed of the reaction, although the nature and total amount of catalyzer present is always the same at the end as at the beginning of the reaction, so far as can be detected.

Cellulose. A substance represented chemically by the expression $C_6H_{10}O_5$. It is the basis of wood structure, excluding a slight amount of mineral ash in the cell walls.

Clinker. A term used herein to designate the more or less molten portions of ash (including some carbon) drawn from the grate and ash pit.

CO. Abbreviation for carbon monoxide.

CO_2. Abbreviation for carbon dioxide.

Coal, air-dried. *See* Air-dried coal.

Coal, dry. *See* Dry coal.

Coal, free-burning. *See* Free-burning coal.

Combustible. A loose expression and misnomer for the phrase "coal free from moisture and ash," sometimes called "pure coal." The pounds of "combustible" used in every steam test have been computed in two ways, as follows:

1. Item 30: Obtained by subtracting from the total pounds of dry coal fired the pounds of ash and combustible drawn out of the ash pit and through the fire doors in cleaning the fire.

2. Item 30*: The weight of the coal fired is corrected for moisture and ash as given by the proximate analysis, thereby giving the pounds of "combustible" fired. From this amount is subtracted the pounds of "combustible" lost in the refuse, giving the total pounds of "combustible" actually ascending from the grate during the test.

Two efficiencies have been figured from these weights of "combustible"—items 72 and 72*.

In this bulletin there are many references to "code item 72*." In reality there is no such item. This 72* item is the one given in the code as item 72, and is the comparable efficiency, because with different grates different amounts of coal might drop into the ash pit and in figuring 72* corrections have been made for this loss. (*See* 72* under "Computations of a steaming test," p. 151.)

Whenever the word "combustible" in this bulletin is in quotation marks it means "coal free from moisture and ash." Quotation marks are employed because the word used in this sense is a misnomer, inasmuch as the oxygen and nitrogen, and perhaps part of the sulphur, do not burn.

Combustion chamber. Strictly, the entire space between the surface of the fuel bed and the area at which the gases enter the boiler; term usually applied, however, to designate the space between the bridge wall and that area.

Conduction. The process of transferring heat by direct contact; as when heat travels along a rod, or from a hot stove lid to a flatiron resting on it.

Convection. The addition to, or removal from, a body of heat, by gases or liquids circulating in direct contact with the body; as the removal of heat from a steam radiator by the circulation of air.

Cones, Seger. *See* Seger cones.

Dissociation. The state of separation of the molecules of a substance into two or more parts. A term used herein to denote effects due to high temperatures.

Dry chimney gases. In all calculations in this bulletin this term includes CO_2, O_2, CO, and N_2 gases.

Dry coal. Coal which has been dried in a very finely powdered condition for one hour at a constant temperature of 105° C. In the expression "B. t. u. per pound of dry coal as fired," however, the "dry coal" is computed from a determination of the moisture in the coal sample.

Efficiencies:

Boiler and grate ("over-all") efficiency, code item 73, denoted by E_1, is the ratio of the heat absorbed by boiler to the potential heat of dry coal fired.

Boiler efficiency, code item 72*, denoted by E_2, is the ratio of the heat absorbed by the boiler to the potential heat of combustible ascending from grate. The combustible in this item is equal to the total dry coal fired, minus the ash by analysis of dry coal, minus the combustible in refuse.

Boiler efficiency, code item 72 (seldom referred to in this bulletin), is the same as 72*, except that the combustible is taken to be equal to total dry coal fired minus the total refuse determined by actual weighing, this total refuse being combustible and ash.

Furnace efficiency, or *per cent of completeness of combustion*, denoted by E_3, is the ratio of the heat actually evolved in the furnace to the potential heat of the combustible ascending from the grate.

EFFICIENCIES—Continued.

True boiler efficiency, denoted by E_4, is the ratio of the heat absorbed by the boiler to the heat in the gases which is available to the boiler, counting only that part of the heat in the gases as available to the boiler which remains after subtracting from the total heat actually generated the amount which is used in heating the gases from atmospheric to steam temperature.

Boiler efficiency corrected, denoted by E_5, is the ratio of the heat absorbed by the boiler to the heat actually evolved in the furnace.

Thermodynamic furnace efficiency is the ratio of the heat made available to the boiler to the potential heat of coal fired.

Thermodynamic efficiency of boiler is the ratio of the heat made available for engine or turbine to the heat available to the boiler.

EMPIRICAL FORMULA. A formula expressing the actual relations between two or more variables and constants, but not founded on known laws. Cf. "Rational formula."

ENDOTHERMIC. An adjective describing a chemical reaction which can take place only by absorbing heat from the surroundings or by reducing the temperature of the reacting matter. The opposite of exothermic.

EXOTHERMIC. An adjective describing a chemical reaction which evolves heat. The opposite of endothermic.

FIXED CARBON. A term applied to that portion of the carbon in a coal left after the "volatilization" process of the proximate analysis. It is obtained by subtracting from 100 the percentages of ash, moisture, and volatile matter.

FREE-BURNING COAL. A term applied to coal which when thrown in the fire burns without the separate pieces of coal fusing together. A noncaking coal.

"FREE" MOISTURE. Moisture which is driven off from coal when subjected to a temperature of 105° C. (221° F.) for one hour.

GRAM MOLECULE. An amount of a substance, in grams, numerically equal to the molecular weight of the substance. For instance, a gram molecule of water is 18 grams, the molecular weight of water being 18 (2 of hydrogen and 16 of oxygen).

HEAT, AVAILABLE. *See* Available heat.

HOOD. The inverted funnel, usually about 4 feet high, between the top of the brick setting and the bottom of the cylindrical smokestack. The flue temperatures and gas samples are taken at the top of the hood, and the stack damper is just above this point.

HYDROGEN, AVAILABLE. *See* Available hydrogen.

HYDROCARBON GASES (HYDROCARBONS). Gases which are distilled from coal when it is heated. They are high in heating value, approximately 1½ times as high in B. t. u. per pound as pure carbon. They usually occur in three forms, expressed by the formulas: C_nH_n, C_nH_{2n}, and C_nH_{2n+2}.

IGNITION TEMPERATURE. The ignition temperature of a substance is that temperature to which it must be raised in the presence of oxygen to cause the two to unite by combustion. This temperature is rather indefinite, as extremely slow union begins far below the point of rapid union. For any one substance there are generally two temperatures, within perhaps 200° F. of each other, at the lower of which the rate of combustion is inappreciable and at the higher of which it is almost infinite.

KINETIC THEORY OF GASES. This theory postulates that gases consist of immense numbers of individual molecules moving among each other with enormous velocities. The sum of the molecular impacts against the sides of a containing vessel constitutes the pressure of a gas. Raising the temperature of a gas increases the molecular speed, and consequently the force of impact.

MASS ACTION, LAW OF. The speed of a chemical reaction is proportional to the product of the weights of reacting substances present, in unit volume, the weight of each substance being expressed in gram molecules.

MOISTURE, "FREE." See "Free" moisture.

O_2. Abbreviation for oxygen (one gaseous molecule).

ORSAT APPARATUS. An instrument for determining the percentages of carbon dioxide, oxygen, and carbon monoxide by absorbing them successively in certain solutions. (See text-books on gas analysis.)

POTENTIAL HEAT. A term applied to the heat in coal as determined by a calorimeter.

PROBABILITY CURVE. The graphic plotting of a certain mathematical equation expressing the likelihood of a quantity being more or less different from what it "ought" to be. (See p. 158.)

PROXIMATE ANALYSIS OF COAL. An empirical method of determining the percentage of "free" moisture, of "volatile matter," of "fixed carbon," and of ash in coal. The method of determination varies somewhat with different chemists.

PYROMETER. An instrument for measuring high temperatures.

RADIATION. The process of transferring heat through space from one body to another without the aid of tangible substance—for example, the transfer of heat from the sun to the earth.

RATIONAL FORMULA. A formula deduced from fundamental laws, as of physics. Cf. "Empirical formula."

REFUSE. Clinker, ash, and unconsumed coal taken from the ash pit and pulled out of the furnace when cleaning fire.

SEGER CONES. Small pyramids made of various chemicals variously mixed. The temperatures of softening of the different cones are fairly well known. Several of them are put into a furnace in a row, each having a melting point intermediate between its neighbors. By watching the curling over of the tips one can form a fairly correct estimate of the average temperature.

STEFAN AND BOLTZMANN'S LAW. The amount of energy radiated by a black-body surface to another body is proportional to the difference of the fourth powers of their absolute temperatures.

STRAIGHT-LINE FUNCTION. A value changing directly or inversely with a variable, so that if simultaneous values are plotted on coordinate paper the points would lie in a straight line.

TEMPERATURE, ABSOLUTE. *See* Absolute temperature.

TEMPERATURE, IGNITION. *See* Ignition temperature.

TEMPERATURE GRADIENT. As used in this bulletin, any continuous change of temperature along a body actively conducting heat.

ULTIMATE ANALYSIS OF COAL. A chemical analysis so made as to give, in percentages, the amounts of carbon, hydrogen, oxygen, nitrogen, and ash in a dry coal. The sulphur is separately determined.

"UNACCOUNTED-FOR LOSS." That percentage of the potential heat of a combustible which remains after deducting all the known expenditures of heat.

VELOCITY. A term loosely applied to the speed of a chemical reaction—for example. combustion. It is proportional at any instant to the rate of formation of new substance by the reaction.

VOLATILE MATTER FROM PROXIMATE ANALYSIS, or "volatile combustible matter," as it is often incorrectly termed, is the mixture of gases, together with some particles of carbon, driven off when a sample of finely ground coal is heated in a closed vessel. This is an arbitrary determination, dependent on the operator and the conditions under which it is made. A committee from the American Chemical Society has suggested a method of volatilization which is generally followed. This method gives fairly concordant results when the same operator, using the same apparatus, makes duplicate determinations on the same sample of coal.

VOLATILE CARBON. A name given to that part of the carbon in coal which is expelled in the process of volatilization by the "standard method" of proximate analysis. It exists in the "volatile matter" resulting from distillation, largely in combination with hydrogen as gaseous hydrocarbons.

WATER OF COMPOSITION. A fictitious value determined by uniting the total oxygen in dry coal with *such a part* of the hydrogen as would be required to form water.

INDEX.

A. Page.

Absorption. *See* Boiler, absorption by.
Absolute temperature, definition of 180
Acknowledgments to those aiding 7–8
Air-dried coal, definition of 180
    See also Coal, air-dried.
Air leakage, data on 67–68
Air supply. *See* Draft.
Alabama coal, smoke test of 57
  No. 3, smoke test of 58
  No. 4, carbon-hydrogen ratio of 72, 77
    smoke test of 58
Arkansas coal, smoke test of 57
  No. 7, smoke test of 58
  No. 7 A, carbon-hydrogen ratio of 71, 77
  No. 8, carbon-hydrogen ratio of 71, 77
    smoke test of 58
  No. 10, smoke test of 58
Ash, amount of, carried over wall, relation of, to unaccounted for loss 168–169
    discussion of 31–33, 38–44
    distribution of 29, 36
    fusing point of, determination of 29
    relation of, to method of burning 43
      to carbon-hydrogen ratio 42
        figure showing 41
      to combustion-chamber temperatures 42
        figure showing 41
      to completeness of combustion 42
        figure showing 41
      to dry-chimney-gas evolution 42
        figure showing 41
      to efficiency 72* 41–42
        figure showing 41
      to flue-gas temperatures 42
        figure showing 41
      to rated capacity 42
        figure showing 41
    relation of clinkers and 36, 39
      figure showing 40
    relation of efficiency 72* to 31, 32–33, 176
      figure showing 33
    relation of efficiency 73 and 39, 176
    relation of size of coal to 42–43, 49
      figure showing 48
    See also Coal, dry, ash plus sulphur in.
Ash-sulphur ratio, relation of, to clinkering 38–39
    relation of efficiency 72* and 93–94

Page.
Available heat, definition of 180
Available hydrogen, definition of 180
    See also Coal, hydrogen in; Hydrogen.
Avogadro's law, statement of 110–180

B.

Baffle, definition of 180
    description of 62
    figure showing 62
    use of 26, 62–63
Barker, Perry, work of 10
Base values, definition of 180
Bibliography 179
Bird, F. J., work of 10
Black body, definition of 180
Boiler and grate efficiency E_1, definition of 181
Boiler efficiency E_4, calculation of 130–136, 143, 147–149, 174
    conclusions on 176
    constant-capacity curves of 143–144, 147–149
      figure showing 144
    curve of 146–149
      figure showing 147
    definition of 95, 141, 182
    relation of, to initial temperature 112–113
    relation of efficiency 72* and 147
      figure showing 147
    relation of probability curve to 146–149
      figure showing 147
Boiler efficiency corrected E_5, calculation of 130–132, 142–143
    constant-capacity curves of 141–143, 147–149
      figure showing 141
    definition of 95, 138, 140, 182
    discussion of 95–99, 103–109, 134–149
    relation of, to ratio of velocity of gas to combustion-chamber temperature 140–141
      figure showing 141
    relation of carbon-hydrogen ratio to 73–74, 78–79
      figures showing 37, 71
    relation of combustion-chamber temperature and 51
    relation of heat evolution to 93–94
      figure showing 93
    relation of smoke to 56
      figure showing 56

Page.

- Boiler efficiency 72, definition of 181
- Boiler efficiency 72,* classification by 40
  - conclusions on 175
  - definition of 137–138, 181
  - relation of, to ash 31, 32–33
    - to ash, figure showing 33
    - to ash-sulphur basis 93, 94
    - to carbon dioxide in flue gases 26–27, 35
      - figure showing 27
    - to carbon monoxide in flue gases 26–27, 65
      - figure showing 27
    - to clinker in refuse 28, 29, 31, 35, 44
      - figure showing 30
    - to sulphur 28–31, 44
      - figure showing 30
    - to unaccounted for loss 139
      - figure showing 138
  - relation of ash to 41–42, 176
    - figure showing 41
  - relation of ash plus sulphur to 94, 95
  - relation of ash-sulphur ratio to 94
  - relation of carbon–available hydrogen ratio to 83–84
    - figure showing 84
  - relation of carbon (volatile)-carbon (total) ratio to 83–85
    - figure showing 86
  - relation of carbon-hydrogen ratio to 70–76, 79–83, 88
    - figure showing 37, 69, 71, 74, 75, 76, 79, 80, 81, 82, 83
  - relation of carbon monoxide in flue gases to 27, 65
    - figure showing 28
  - relation of clinker in refuse to 44
  - relation of combustion-chamber temperature to 22–24, 50
    - figure showing 25
  - relation of fixed carbon to 90
    - figure showing 91
  - relation of hydrogen to 83
    - figure showing 84
  - relation of hydrogen–available hydrogen ratio to 85–86
    - figure showing 87
  - relation of iron-ash ratio to 34–35, 37–38
    - figure showing 35
  - relation of moisture to 32, 176
    - figure showing 33
  - relation of nitrogen in flue gases to 64–65
    - figure showing 28
  - relation of oxygen in combustible and 92–93
    - figure showing 92
  - relation of probability curve and 146–149
    - figure showing 147

Page.

- Boiler efficiency 72*, relation of rate of combustion to 16–17
  - relation of rate of combustion to, figure showing 17
  - relation of rate of heat evolution to 15–17
    - figure showing 14
  - relation of rated capacity to 52
  - relation of size of coal to 46–51
    - figure showing 46, 48
  - relation of sulphur in coal to 43–44, 176
    - figures showing 43
  - relation of true boiler efficiency (E_4) and 147
    - figure showing 147
  - relation of volatile matter to 89–90
    - figure showing 90
  - relation of washing to 176
  - relation of wind to 167–168
  - test of 26–32
- Boiler efficiency 72* at about rated capacity, relation of carbon-hydrogen ratio to 70
    - figure showing 69
- Boiler efficiency 73, definition of 181
  - relation of ash and 39–40, 176
    - figure showing 40
- Boiler tubes. *See* Tubes.
- Boilers, air leakage of, data on 67–68
  - cost of 177
  - dimensions of 173
    - figure showing 174
  - efficiency of. *See* Boiler efficiency.
  - heat absorption by 105–112
    - factors of, relation of, to furnace temperature 113–114
      - relation of, to furnace temperature, figure showing 15
    - Perry's theory of 109–112
      - test of 132–134
    - relation of, to physical attributes 112–113
      - to total available heat 130–131, 137
        - figure showing 131
    - relation of carbon-hydrogen ratio to 37
      - figure showing 37
    - relation of density of gas to 109, 113–114
      - figure showing 15
    - relation of gas velocity to 109–110, 113–118, 130–132
      - figure showing 131
    - relation of specific heat of gases to 110–112, 132–137
    - relation of water circulation and 120–121
    - theoretical curves of 27–28
      - figure showing 29

Page.

- Boilers, heat absorption by, theory of 109–112
  - heat absorption by, theory of, application of 118–120
    - theory of, modifications of 125–132, 134–137
    - variation in, along a fire tube 121–125
      - along a fire tube, figures showing 123–124
    - *See also* Heat balance.
  - heat losses of 99
  - improvement of 177
  - insulation of, by soot, etc. 125–132
  - low pressure in, effect of, on economy 102–105
  - parts of 95
  - rated capacity of. *See* Capacity, rated.
  - type of 8
  - water circulation in, effect of firing and cleaning fires on 162
    - effect of firing and cleaning fires on, figure showing 162
    - indicator for, description of 160–162
      - figure showing 161
    - rate of, relation of rate of steaming to 16, 163
      - figure showing 16
    - relation of heat absorption and 120–121
- Boltzman' and Stephan's law, statement of 112, 183
- Brazil coal, smoke test of 57
  - No. 1, clinker in 34
  - smoke test of 58
- Breckenridge, L. P., work of 10, 174
- Briquetting, effects of 50, 177
- British thermal units, definition of 180
  - *See also* Heat.

C.

- Caking, definition of 180
- Calcium sulphate, occurrence of 38
  - *See also* Sulphur.
- Campbell, M. R., carbon-hydrogen classification by 68
- Capacity, rated, definition of 180
  - discussion of 51–52
  - relation of, to combustion-chamber temperature 52
    - to efficiency 52
    - to ratio of combustion-chamber temperature minus steam to flue gas minus steam 137
      - figure showing 136
  - relation of ash to 42
    - figure showing 41
  - relation of carbon-hydrogen ratio to 69, 73

Page.

- Capacity, rated, relation of carbon-hydrogen ratio to, figure showing 37, 69, 71, 74, 75, 76, 79, 80, 81, 82
  - relation of clinker in refuse to, figure showing 36
  - relation of combustion-chamber temperature to 20–21, 25–26
    - figures showing 21, 25
  - relation of fixed carbon to 90
    - figure showing 91
  - relation of heat evolution to 15, 94
    - figure showing 14, 93
  - relation of hydrogen-available hydrogen ratio to 86
    - figure showing 87
  - relation of rate of combustion to 17, 176
    - figure showing 17
  - relation of revolutions per minute and 16, 163
    - figure showing 16
  - relation of size of coal to 46, 48
    - figure showing 46, 48
- Carbon, fixed, classification by 87–88
  - definition of 180
  - nature of 59
  - relation of, to completeness of combustion 92
    - to completeness of combustion, figure showing 91
    - to combustion-chamber temperature 90–91
      - figure showing 91
    - to efficiency 72* 90
      - figure showing 91
    - to flue-gas temperature 91
      - figure showing 91
    - to gas evolution 92
      - figure showing 91
    - to rated capacity 90
      - figure showing 91
  - relation of smoke to 57
    - figure showing 56
- Carbon, volatile, definition of 59, 183
- Carbon (volatile)—total carbon ratio, relation of, to efficiency 72* 83–85
  - relation of, to efficiency 72*, figure showing 86
- Carbon–available hydrogen ratio, definition of 180
  - *See also* Coal, dry; Coal as received.
- Carbon dioxide. *See* Gases, carbon dioxide in.
- Carbon-hydrogen ratio, basis of 68–69
  - classification by 68–81
  - definition of 180
  - *See also* Coal as received; Coal, dry.
- Carbon monoxide, definition of 180
  - *See also* Gases, carbon monoxide in.

Page.

Carbon monoxide loss, relation of carbon-hydrogen ratio to 73, 74–80
  relation of carbon-hydrogen ratio to, figures showing 37, 71, 74, 75, 76, 79, 80, 81, 82
  relation of clinker and 35
  relation of hydrogen-available hydrogen ratio to 86
    figure showing 87
  relation of rate of combustion to 12
    figure showing 12
  relation of heat evolution to 14–15
    figure showing 13
Catalyzer, definition of 180
Cellulose, definition of 180
Chimney gases. *See* Gases.
Circulation, water. *See* Boiler, water circulation in.
Cleaning fires, effect of, on water circulation 162
  effect of, on water circulation, figure showing 162
  time required for 38, 39
Clinker, definition of 180
  See also Refuse, clinker in.
CO. *See* Carbon monoxide.
CO_2. *See* Carbon dioxide.
Coal, ash in. *See* Ash.
  ash-sulphur ratio of, relation of efficiency and 93–94
  burning of, relation of ash and clinkers to 43
  classification of 17, 68–94
  clinker from. *See* Refuse, clinkers in.
  combustion of forecasting of 10
  crushing of, advantage of 50–51
  distillation of 58–59
  iron in, relation of, to clinkers 35, 38
  nature of 58
  size of, effects of 45–51
    relation of ash and 42–43
    relation of clinkers and 35–37, 40–41, 47
    relation of nitrogen in flue gases to 65
      figure showing 28
    See also Coal, dry.
  sizing of 45–46
  sulphur in. *See* Sulphur.
  washing of, relation of, to efficiency 72* 176
  See also Combustible.
Coal, air dried, classification of, on carbon-hydrogen ratio 68–70
  definition of 180
Coal as received, ash in. *See* Ash.
  carbon-available carbon ratio of, definition of 180
    relation of, to efficiency 72* 83
      figure showing 84

Page

Coal as received, carbon-hydrogen ratio of 70–7
  carbon-hydrogen ratio of, relation of, to CO loss 73, 74–7
    relation of, to CO loss, figure showing 37, 71, 74, 75, 7
      to combustion-chamber temperature 75–7
        figures showing 71, 74, 75, 76
      to completeness of combustion 82
      to efficiency 72* 70–76, 82–83
        figures showing 37, 69, 71, 74, 75, 76, 83
      to efficiency 72* at about rated capacity 70
        figure showing 69
      to gases evolved 73
        figures showing 37, 71, 74, 75, 7
      to heat evolved 7
        figures showing 7
      to rated capacity 69, 7
        figures showing 6, 71, 74, 75, 7 6
      to hydrogen-available hydrogen ratio 76– 7
        figures showing 6
      to theoretical boiler efficiency 73–74
        figures showing 71
    See also Carbon-hydrogen ratio; Coal, dry.
  classification of 70–77
  hydrogen in. *See* Hydrogen.
  hydrogen available hydrogen ratio of, relation of, to carbon-hydrogen ratio 76–77
    relation of, to carbon-hydrogen ratio, figure showing 7
  moisture in 3
    relation of efficiency and 32, 1 17
      figure showing 3
Coal, dry, ash in. *See* Ash.
  ash plus sulphur in, relation of, to efficiency 72* 9
  ash-sulphur ratio of, relation of efficiency 72* and 93, 9
  carbon-hydrogen ratio of 77–7
    relation of, to CO loss 79–8
      to CO loss, figure showing 37, 79, 80, 81, 82
      to chimney-gas evolution 79–81
        figure showing 37, 79, 80, 81, 82
      to clinker in refuse 78
        figure showing 37

Page.

- Coal, dry, carbon-hydrogen ratio of, relation of, to combustion-chamber temperature 79–80, 88
  - carbon-hydrogen ratio of, relation of, to combustion-chamber temperature, figures showing 37, 79, 80, 81, 82
    - relation of, to efficiency 72* 79–81, 88
      - to efficiency 72, figures showing 87, 79, 80, 81, 82
      - to gases, evolved, figures showing 79, 80, 81, 82
      - to hydrogen - available hydrogen ratio 77–81
        - figures showing 79, 80, 81, 82
      - to rated capacity, figures showing 37, 79, 80, 81, 82
      - to theoretical boiler efficiency 78–79
        - figure showing 37
    - relation of ash to 42
      - figure showing 41
    - relations of size of coal and 46–48, 78
      - figure showing 37, 46, 48
    - *See also* Carbon-hydrogen ratio; Coal as received.
  - classification of, on carbon-hydrogen ratio 77–82
    - on efficiency basis 40
  - definition of 181
  - hydrogen in. *See* Hydrogen.
  - hydrogen – available hydrogen ratio of 85–88
    - relation of, to CO loss 86
      - to CO loss, figure showing 87
      - to combustion-chamber temperature 85–86
        - figure showing 87
      - to rated capacity 86
        - figure showing 87
      - to efficiency 72* 85–86
        - figure showing 87
      - to carbon-hydrogen ratio 79–81
        - figure showing 37, 80, 81, 82
  - iron-ash ratio of, relation of, to efficiency 34–35, 37–38
    - relation of, to efficiency, figure showing 35
  - oxygen in, relation of smoke to 57
    - relation of smoke to, figure showing 56
  - size of, relation of, to ash 49
    - relation of, to ash, figure showing 48
      - to carbon - hydrogen ratio 46–48
        - figures showing 46, 48

Page.

- Coal, size of, relation of, to chimney-gas evolution 46, 48–49
  - size of, relation of, to chimney-gas evolution, figure showing 46, 48
    - relation of, to combustion-chamber temperature 46, 47, 50
      - to combustion-chamber temperature, figure showing 46
      - to completeness of combustion 46
        - figure showing 46
      - to draft 48, 176
        - figure showing 48
      - to efficiency 72* 46–51
        - figure showing 46, 48
      - to flue-gas temperature 46
        - figure showing 46
      - to rated capacity 46, 48
        - figure showing 48
      - to rate of combustion 48, 176
        - figure showing 46, 48
    - *See also* Coal.
  - sulphur in. *See* Sulphur.
- Coal, pulverized, burning of 50–51
- Combustible, computation of 181
  - definition of 181
  - hydrogen in. *See* Hydrogen.
  - oxygen in. *See* Oxygen.
  - relation of, to gas evolution 167
  - volatile matter in, classification by 87–90
    - relation of, to combustion-chamber temperature 90
      - to combustion-chamber temperature, figure showing 89
    - relation of, to efficiency 72* 89–90
      - figure showing 89
- Combustible in refuse, relation of clinkers to 38
- Combustion, completeness of, definition of 172, 181
  - completeness of 10
    - relation of ash to 42
      - figure showing 41
    - relation of CO₂ in flue gases to 65-66
      - figure showing 51
    - relation of carbon-hydrogen ratio to 82
    - relation of draft and 172
    - relation of fixed carbon to 92
      - figure showing 91
    - relation of heat evolution to 94
      - figure showing 93
    - relation of size of coal to 46
      - figure showing 46
    - relation of sulphur to 44
      - figure showing 43
    - relation of temperature and 172
    - *See also* Furnace efficiency

E₃.

Page.

- **Combustion, products of, relation of, to draft** 15–16
  - **products of, relation of, to draft, figure showing** 15
    - **temperature of, relation of, to draft** 159–160
      - **figure showing** 160
  - **rate of** 60–61, 176
    - **relation of, to draft** 176
      - **to rated capacity** 16–17, 176
        - **figure showing** 17
      - **to flue-gas temperature** 11
        - **figure showing** 12
      - **to various losses** 11–13
        - **figure showing** 12
    - **relation of combustion-chamber temperature to** 19–20
      - **figure showing** 20
    - **relation of size of coal to** 48, 176
      - **figure showing** 48
    - **results of, forecasting of** 10
    - **temperatures of, calculation of** 9–10
      - **relation of draft and completeness of combustion and** 172
- **Combustion chamber, baffle wall in.** *See* **Baffle.**
  - carbon monoxide in 166–167
    - relation of smoke and 166–167
  - definition of 181
  - description of 59
  - gases in, analyses of 59–60
    - volumetric composition of 61
    - *See also* Gases.
  - temperature of, discussion of 18–26
    - relation of, to carbon dioxide in flue gas 24–25
      - to carbon dioxide in flue gas, figure showing 25
      - to efficiency 72* 20–21, 23–24, 50, 51
        - figures showing 21, 25
      - to flue-gas temperature 22–23
        - figure showing 24
      - to heat balance 63
        - figure showing 63
      - to losses 20–21, 63
        - figure showing 21, 63
      - to rate of combustion 19–20
        - figure showing 20
      - to rated capacity 20–21, 25–26
        - figure showing 21, 25
      - to theoretical heat evolution 19–20
        - figure showing 20
    - relation of ash to 42
      - figure showing 41
    - relation of CO_2 to 21–22
      - figure showing 22, 23

Page.

- **Combustion chamber, temperature of, relation of carbon-hydrogen ratio to** 75–76, 79, 80, 88
  - **temperature of, relation of carbon-hydrogen ratio to, figure showing** 37, 71, 74, 75, 76, 79, 80, 81, 82
    - **relation of CO to** 21–22, 65
      - **figure showing** 22, 23
    - **relation of clinkers in refuse to** 44
      - **figure showing** 36
    - **relation of fixed carbon to** 90–91
      - **figure showing** 91
    - **relation of flue-gas composition to** 21–22
      - **figures showing** 22, 23
    - **relation of heat evolution to, figure showing** 93
    - **relation of hydrogen–available hydrogen ratio to** 85–86
      - **figure showing** 87
    - **relation of oxygen in flue gas to** 21–22
      - **figures showing** 22, 23
    - **relation of rated capacity to** 52
    - **relation of size of coal to** 46, 47, 50
      - **figure showing** 46
    - **relation of smoke to** 57
      - **figure showing** 56
    - **relation of sulphur to** 44
      - **figure showing** 43
    - **relation of volatile matter to** 90
      - **figure showing** 89
  - **temperature of, minus steam, relation of, to flue gas minus steam** 132–134
    - **minus steam, relation of, to flue gas minus steam, figure showing** 133
      - **relation of, to flue gas minus steam, modifications of** 134–137
- **Combustion space, description of** 59
  - **function of** 59
- **Conduction, definition of** 181
- **Cones, Seger, definition of** 183
- **Convection, definition of** 181

D.

- **Data, reliability of** 149–153
- **Density.** *See* **Gases, density of.**
- **Dissociation.** *See* **Gases, dissociation of.**

Page.
raft, in stack, relation of, to gas evolution 167
  in stack and over fire, difference of 167
    relation of, to chimney-gas evolution 66–68
      to chimney-gas evolution, figure showing 66
      to size of coal 48
        figure showing 48
  over fire, relation of availability of heat to 137
    relation of availability of heat to, figure showing 138
    relation of completeness of combustion and 172
    relation of products of combustion to 15–16
      figure showing 15
    relation of rate of combustion and 176
    relation of temperature of products of combustion to 159–160, 172
      figure showing 160
Dry chimney gases, definition of 181
  See also Gases.
Dry coal. *See* Coal, dry.

E.

Efficiencies, thermodynamic, definition of 95–97, 182
  definition of, figure illustrating 96
Empirical formula, definition of 182
ndothermic, definition of 182
xothermic, definition of 182

F.

ire tubes, absorption of heat by, increase in 124–125
  absorption of heat by, variations in 121–125
    variations in, figures showing 123, 124
  incasing of 164
  See also Boilers.
ires, cleaning of, time of 38, 39
iring, effect of, on water circulation 162
  effect of, on water circulation, figure showing 162
  method of, recommendation of 177
ixed carbon. *See* Carbon, fixed.
letcher, C. J., work of 10
lorida coal, smoke test of 57
lue gases. *See* Gases.
ree-burning coal, definition of 181
ree moisture, definition of 182
uel adaptation, principles of 10

Page.
Furnace, adaptation of, to burning slack 50
  gases of. *See* Gases, furnace.
  heat evolution in, calculation of 137
  heat losses in 99
  improvement of 178
  initial temperature of, modifications due to 134–137
  relation of, to economy 100–102
  parts of 59
  temperatures of 26
Furnace efficiency E_3, definition of 138, 172, 181
  discussion of 95–99, 137–149
  figure showing 96
  See also Combustion, completeness of.

G.

Galt, Ralph, work of 10
Gas sampler, description of 154–155, 156
  figure showing 24, 157
  readings of 155–156
Gases, analyses of 59–60, 100
  carbon dioxide in, dissociation of 153–154
    dissociation of, figure showing 154
    relation of, to combustion-chamber temperature 21–22
      to combustion-chamber temperature, figures showing 22, 23
      to completeness of combustion 65–66
        figure showing 51
      to efficiency 72* 27, 35
        figure showing 27
    relation of combustion-chamber temperature to 24–25
      figure showing 25
    relation of efficiency 72* to 26–27
      figure showing 27
  $CO_2 + O_2 + CO$ in, relation of available hydrogen to 165–166
    variation of 164–166
    See also Orsat apparatus.
  carbon monoxide in, relation of, to combustion-chamber temperature 21–22, 65
    relation of, to combustion-chamber temperature, figures showing 22, 23
      to efficiency 72* 26–27, 65
        figure showing 27, 28
      to smoke 57, 167
        figure showing 56
    relation of efficiency 72* to 26–27, 65
      figure showing 27
    relation of size of coal to 49, 50
    significance of 65

Page.

- Gases, composition of 61, 100–101
  - composition of, relation of, to combustion-chamber temperature 21–22
    - relation of, to combustion-chamber temperature, figures showing 22, 23
  - density of, relation of heat absorption to 109, 113–114
    - relation of heat absorption to, figure showing 15
  - dislodgment of from boiler surface 109–111
    - figure showing 110
  - dissociation of, definition of 181
    - processes of 153–154
      - figure showing 154
  - evolution of, relation of ash to 42
    - relation of ash to, figure showing 41
    - relation of carbon-hydrogen ratio to 73, 79–81
      - figure showing 37, 71, 74, 75, 76, 79, 80, 81, 82
    - relation of clinker in refuse to 44
      - figure showing 36
    - relation of draft to 66–68, 167
      - figure showing 66
    - relation of fixed carbon to 92
      - figure showing 91
    - relation of heat evolution to 94
      - figure showing 93
    - relation of, rate of combustion to 11
      - figure showing 12
    - relation of rate of heat evolution to 14
      - figure showing 13
    - relation of size of coal to 46, 48–49
      - figure showing 46, 48
    - relation of sulphur to 44
      - figure showing 43
  - losses in 142
    - relation of, to initial temperature 100–102
    - to initial temperature, figure showing 102
    - *See also* CO loss; CO_2 loss.
  - mixing of. *See* Mass action, law of.
  - nitrogen in, relation of, to efficiency 64–65
    - relation of, to efficiency, figure showing 28
    - to size of coal 65
      - figure showing 28
  - oxygen in, relation of, to combustion-chamber temperature 21–22

Page.

- Gases, oxygen in, relation of, to combustion-chamber temperature, figures showing 22, 23
  - specific heat of, relation of, to heat absorption 110–112
  - temperature gradients of 126–127
    - figure showing 127
  - temperature of, relation of, to heat absorption 110–112, 132–137
    - relation of ash to 42
      - figure showing 41
    - relation of combustion-chamber temperature to 22–23
      - figure showing 24
    - relation of fixed carbon to 91
      - figure showing 91
    - relation of rate of combustion to, figure showing 12
    - relation of rate of heat evolution to, figure showing 13
    - relation of size of coal to 46
      - figure showing 46
  - temperature of, minus steam, ratio of combustion-chamber temperature to 132–134
      - figure showing 133
      - modification of 134–137
    - minus steam, relation of, to rated capacity 137
  - velocity of, ratio of, to combustion-chamber temperature, relation of, efficiency E_5 to 141–142
    - ratio of, to combustion-chamber temperature, relation of efficiency E_5 to, figure showing 141
    - relation of, to heat absorption 109–110, 113–118, 130–132
      - to heat absorption, figure showing 131
  - volumetric composition of 61
- Glossary 180–183
- Gram molecule, definition of 182
- Grate, function of 59
- Green, C. H., work of 10

H.

- Heat, absorption of 95–149
  - absorption of. *See also* Boiler, absorption of heat by; Boiler efficiency.
  - availability of, relation of, to draft 139
    - relation of, to draft, figure showing 138

Page.

- t, evolution of 93–94
  - rate of 13–18
    - relation of, to efficiency 72* 15–17
      - to efficiency 72*, figure showing 14
      - to flue-gas temperature 14
        - figure showing 13
      - to various losses 13–15
        - figure showing 13
      - to rated capacity 13
        - figure showing 14
    - relation of combustion-chamber temperature to 19–20
      - figure showing 20
    - relation of carbon-hydrogen ratio to 73
      - figure showing 71
  - relation of, to completeness of combustion 94
    - to completeness of combustion, figure showing 93
      - *See also* Combustion, completeness of; Furnace efficiency E_3.
    - to combustion-chamber temperature, figure showing 93
    - to efficiency 72* 93–94
      - figure showing 93
    - to gas evolution 94
      - figure showing 93
    - to rated capacity 94
      - figure showing 93
- loss of, unaccounted for, definition of 183
  - unaccounted for, estimation of 156–158
    - explanation of 64
    - relation of, to ash passing over wall 168–169
    - relation of combustion-chamber temperature to 63
      - figure showing 63
    - relation of efficiency 72* to 137
      - figure showing 138
    - relation of rate of combustion to 12
      - figure showing 12
    - relation of rate of heat evolution to 14
      - figure showing 13
    - relation of smoke to 56–57
      - figure showing 56
    - plus loss up stack, relation of combustion-chamber temperature to 20–21, 63

Page.

- Heat, loss of, unaccounted for, plus loss up stack, relation of combustion-chamber temperature to, figure showing 21–63
  - loss of, unaccounted for, plus loss up stack, relation of heat evolution to 14
    - unaccounted for, plus loss up stack, relation of heat evolution to, figure showing 13
    - up stack, relations of, to rate of combustion 11–13
      - relations of, to rate of combustion, figure showing 12
        - to rate of heat evolution 14–15
          - figure showing 13
      - relation of combustion-chamber temperature to 63
        - figure showing 63
      - relation of rate of heat evolution to 14–15
        - figure showing 13
  - transmission of. *See* Boilers, absorption of heat by.
- Heat, available, definition of 180
- Heat balance, forms of 139
  - forms of, discussion of 139–141
- Hood, definition of 182
- Hydrogen, available, definition of 180
  - relation of, to efficiency 72* 83
    - to efficiency 72*, figure showing 84
    - to flue-gas total 165–166
  - relation of smoke to 57
    - figure showing 56
  - *See also* Coal as received; Coal, dry.
- Hydrogen–available hydrogen ratio. *See* Coal as received; Coal, dry.

I.

- Ignition temperature, definition of 182
- Illinois coal, smoke test of 57
  - tests on 49–50
  - use of, in high-temperature work 159–160
  - No. 6B, smoke test of 58
  - No. 7C, carbon-hydrogen ratio of 72, 78
  - No. 7D, carbon-hydrogen ratio of 72, 78
  - No. 9B, carbon-hydrogen ratio of 72, 78
  - No. 11A, carbon-hydrogen ratio of 72, 77
  - No. 11C, smoke test of 58
  - No. 12, carbon-hydrogen ratio of 72, 78
  - No. 13, carbon-hydrogen ratio of 72, 77

Page.

- Illinois coal, No. 14, carbon-hydrogen ratio of 72, 78
  - No. 15, carbon-hydrogen ratio of 72, 78
  - No. 16, carbon-hydrogen ratio of 72, 77
  - No. 18, carbon-hydrogen ratio of 72, 78
  - No. 19A, carbon-hydrogen ratio of 72, 77
  - No. 19B, carbon-hydrogen ratio of 72, 77
  - No. 20, carbon-hydrogen ratio of 72, 78
    - smoke test of 58
  - No. 21, carbon-hydrogen ratio of 72, 78
    - smoke test of 58
  - No. 22A, carbon-hydrogen ratio of 72, 78
  - No. 23A, carbon-hydrogen ratio of 72, 78
    - smoke test of 58
  - No. 24B, carbon-hydrogen ratio of 72, 78
  - No. 25, carbon-hydrogen ratio of 72, 78
    - smoke test of 58
  - No. 26, carbon-hydrogen ratio of 72, 78
  - No. 27, carbon-hydrogen ratio of 72, 78
- Indiana coal, smoke test of 57
  - tests on 49–50
  - No. 3, carbon-hydrogen ratio of 72, 78
  - No. 4, carbon-hydrogen ratio of 72, 78
  - No. 5, carbon-hydrogen ratio of 72, 78
  - No. 6, carbon-hydrogen ratio of 72, 78
  - No. 7A, carbon-hydrogen ratio of 72, 78
  - No. 7B, carbon-hydrogen ratio of 72, 78
    - smoke test of 58
  - No. 8, carbon-hydrogen ratio of 72, 78
  - No. 9, carbon-hydrogen ratio of 72, 78
  - No. 9B, carbon-hydrogen ratio of 78
  - No. 10, carbon-hydrogen ratio of 72, 78
  - No. 11, carbon-hydrogen ratio of 72
  - No. 12, carbon-hydrogen ratio of 72, 78
- Initial temperature, definition of 140
  - *See* Furnace, initial temperature of.
- Iron in coal, clinkering due to 34
  - *See also* Coal, iron in.

K.

- Kansas coals, clinkering of 38–39
  - smoke test of 57
  - No. 6, carbon-hydrogen ratio of 72, 77
- Kentucky coal, smoke test of 57
  - tests on 49–50
  - No. 1C, carbon-hydrogen ratio of 72, 77
  - No. 5, carbon-hydrogen ratio of 72, 77
  - No. 6, carbon-hydrogen ratio of 72, 77
  - No. 7, carbon-hydrogen ratio of 77
- Kinetic theory statement of 182
- Kreisinger, Henry, work of 7, 10
- Kuss, R. H., work of 10

L.

- Lignites, firing of 177
- Lord, N. W., work in charge of 7, 29
- Loss unaccounted for, definition of 183
  - *See also* Heat, loss of, unaccounted for.
- Loss up stack. *See* Heat, loss of, up stack.
- Low-pressure steam, use of 102–104

Page.

M.

- Maryland coal, smoke test of 57
  - No. 1, carbon-hydrogen ratio of 71, 77
    - smoke test of 58
- Mass action, law of 170–172, 182
- Missouri coal, smoke test of 57
  - No. 5, carbon-hydrogen ratio of 72, 78
    - smoke test of 58
  - No. 6, carbon-hydrogen ratio of 72, 78
  - No. 7, carbon-hydrogen ratio of 72, 78
- Moisture. *See* Coal, moisture in; Free moisture.

N.

- Negative results, value of 9–10
- Nerst, Walther, on dissociation 153
- New Mexico coal, smoke test of 57
  - No. 3A, clinker in 34
  - No. 3B, clinker in 34
  - No. 4A, clinker in 34
  - No. 5, clinker in 34
    - smoke test of 58
- Nitrogen. *See* Gases, nitrogen in.
- North Dakota coal, smoke test of 57
  - No. 3, smoke test of 58

O.

- Observations, reliability of 149–153
- Ohio coal, smoke test of 57
  - No. 1, carbon-hydrogen ratio of 72, 78
  - No. 2, carbon-hydrogen ratio of 72, 78
  - No. 3, carbon-hydrogen ratio of 72, 77
  - No. 4, carbon-hydrogen ratio of 72, 77
  - No. 5, carbon-hydrogen ratio of 71, 72, 77
  - No. 6, carbon-hydrogen ratio of 72
  - No. 7, carbon-hydrogen ratio of 72, 78
  - No. 8, carbon-hydrogen ratio of 72, 78
  - No. 8, test of, temperature of, figure showing 18
  - No. 9A, carbon-hydrogen ratio of 72, 77
  - No. 9B, carbon-hydrogen ratio of 72, 78
- Optical pyrometer. *See* Pyrometer.
- Orsat apparatus, definition of 183
  - totals in 164–166
- Oxygen in coal, relation of efficiency 72* and 92–93
  - relation of efficiency 72* and, figure showing 93
  - relation of smoke to 57
    - figure showing 56
  - *See also* Gases, oxygen in.

P.

- Pahmeyer, F. O., work of 10
- Park, W. W., work of 10
- Pennsylvania coal, smoke test of 57
  - No. 4, carbon-hydrogen ratio of 71, 77
  - No. 5, carbon-hydrogen ratio of 72, 77
  - No. 6, carbon-hydrogen ratio of 71, 77
  - No. 7, carbon-hydrogen ratio of 71, 72, 77
    - clinker in 33, 34

Page.
Pennsylvania coal No. 8, carbon-hydrogen ratio of 71, 77
  smoke test of 58
  No. 10, carbon-hydrogen ratio of 72, 77
Perry, John, formulas of 108–112
  formulas of, temperature test of 132–134
Pope, G. S., work of 10
Post, R. H., work of 10
Potential heat, definition of 183
Probability curves, definition of 158–159, 183
  figure showing 158
  relation of, to efficiency 72* 146–149
    to efficiency 72*, figure showing 147
    to true boiler efficiency E_4 146–149
      figure showing 147
Proximate analysis, definition of 183
Pyrites, nature and occurrence of 38
  See also Sulphur.
Pyrometer, optical, check by 132–134
  check on 9
  description of 52–53, 183
  figure showing 19
  temperatures by, check on 55, 106
    check on, figure showing 55
Pyrometry, discussion of 52, 55

R.

Radiation, definition of 183
  estimation of 143–146
Randall, D. T., work of 7
Rated capacity developed. *See* Capacity, rated.
Rational formula, definition of 183
Ray, W. S., introduction by 9–11
  work of 7, 10–11
Refuse, clinker and combustible in, relations of 38
  clinker in 28–38, 40–41
    causes of 34
    prevention of, by method of burning 43
      by limestone 39
      by steam jet 38–39
    relation of, to chimney gases produced 44
      to chimney gases produced, figure showing 36
      to combustion-chamber temperature 44
        figure showing 36
      to efficiency 72* 44
      to rated capacity, figure showing 36
      to size of coal 40–41
    relation of ash and 36, 39
    relation of ash-sulphur ratio to 38
    relation of carbon-hydrogen ratio to, figure showing 37

Page.
Refuse, clinker in, relation of carbon monoxide and 35
  clinker in, relation of efficiency to 28–29, 31, 35
    relation of efficiency to, figure showing 30
    relation of iron to 35, 38
    relation of size of coal and 35–36, 47
      figure showing
    relation of sulphur to 39, 44
  combustible in, relation of clinkers to 38
  definition of 183
Revolutions per minute, relation of rated capacity and 16, 163
  relation of rated capacity and, figure showing 163
Rhode Island coal, smoke test of 57
  No. 1, smoke test of 58
Ryder, G. E., work of 10

S.

Scale, insulation of water in boiler by 125–126
Seger cones, definition of 183
Slack coal, utilization of 50–51
Smith, L. H. H., on clinkers 38
Smoke, discussion of 56–58
  relation of, to efficiency 72* 56
    to efficiency 72*, figure showing 56
    to CO in combustion chamber 167
    to CO in flue gases 57
      figure showing 56
    to combustion-chamber temperature 57
      figure showing 56
    to fixed carbon 57
      figure showing 56
    to hydrogen in combustible 57
      figure showing 56
    to oxygen in coal 57
      figure showing 56
    to rate of combustion 176
    to unaccounted-for loss 56–57
      figure showing 56
Soot, insulation by 125–126, 176
Stack loss. *Sec* Heat, loss of, up stack.
Steam, bubbles of, formation of, effect of, on heat transmission 125-126
Steam, low pressure, use of 102–105
Steam jet, prevention of clinkers by 38–39
Steaming, rate of, effect of, on circulation of water 16, 163
  rate of, effect of, on circulation of water, figure showing 16
Stephan and Bolzmann's law, statement of 112, 183
Stowe, L. R., work of 10
Straight-line function, definition of 183

Page.

- Sulphur, relation of, to chimney-gas evolution 44
  - relation of, to chimney-gas evolution, figure showing 43
  - relation of, to clinkering 38–39, 44
    - to combustion-chamber temperature 44
      - figure showing 37
    - to completeness of combustion 44
      - figure showing 43
  - relation of efficiency 72* and 28–31, 43–44, 176
    - figure showing 30, 43

T.

- Temperature. *See* Furnace; Combustion chamber; Gases; etc.
- Temperature, absolute, definition of 180
- Temperature, ignition, definition of 182
- Temperature, initial. *See* Furnace, initial temperature of.
- Temperature gradient, definition of 183
- Tennessee coal, smoke test of 57
  - No. 1, carbon-hydrogen ratio of 72, 78
  - No. 2, carbon-hydrogen ratio of 72, 77
  - No. 3, carbon-hydrogen ratio of 72, 78
  - No. 4, carbon-hydrogen ratio of 72, 78
  - No. 5, carbon-hydrogen ratio of 72, 77
    - smoke test of 58
  - No. 6, carbon-hydrogen ratio of 72, 77
    - smoke test of 58
  - No. 7 A, carbon-hydrogen ratio of 72, 78
  - No. 8 A, smoke test of 58
  - No. 8 B, smoke test of 58
  - No. 9, carbon-hydrogen ratio of 72, 77
    - smoke test of 58
- Tests, data of, relations of 11–58
  - object of 7
  - repetition of, effect of 31–32
  - unreliability of 9
- Texas coal, smoke test of 57
  - No. 4, clinker in 34
    - smoke test of 58
- Thermodynamic efficiencies, definition of 95–97, 182
  - figure showing 96
- Thermoelectric couple, description of 53–55
- Tiles, tube, forms of 164
- Tubes, boiler, absorption of heat by, increase in 124–125
  - absorption of heat by, variation in 121–125
    - variation in, figures showing 123, 124
  - incasing of 164
  - *See also* Boilers.
- Turbines, low-pressure steam in 103–105, 178
- Turbines, low-pressure steam in, figure showing 105
- True boiler efficiency. *See* Boiler efficiency E_4.

U.

- Ultimate analysis, definition of 183
- Unaccounted for loss. *See* Heat, loss of, unaccounted for.
- Utah coal, smoke test of 57

V.

- Velocity, definition of 183
- Virginia coal, smoke test of 57
  - No. 1 B, carbon-hydrogen ratio 72
  - No. 2, carbon-hydrogen ratio of 72, 77
  - No. 3, carbon-hydrogen ratio of 71, 77
  - No. 4, carbon-hydrogen ratio 72
    - clinkering of 38–39
- Volatile carbon, definition of 59, 183
- Volatile matter, definition of 183
  - nature of 59
  - *See also* Carbon, volatile; Combustible.

W.

- Wanner pyrometer. *See* Pyrometer.
- Wartenberg, Doctor, on dissociation of gases 153–154
- Washington coal, smoke test of 57
  - No. 1 B, carbon-hydrogen ratio of 78
    - clinker in 34
  - No. 2, carbon-hydrogen ratio of 72, 78
- Water circulation. *See* Boilers, water circulation in.
- Water of composition, definition of 183
- Weeks, H. W., work of 7, 10
- West Virginia coal, smoke test of 57
  - No. 13, carbon-hydrogen ratio of 72, 77
  - No. 14, carbon-hydrogen ratio of 71, 77
    - clinkering of 38–39
  - No. 15, carbon-hydrogen ratio of 72, 77
    - clinkering of 38–39
  - No. 17, carbon-hydrogen ratio of 71, 77
  - No. 18, carbon-hydrogen ratio of 71, 77
  - No. 19, carbon-hydrogen ratio of 71, 77
    - test of, temperature of, figure showing 18
    - smoke test of 58
  - No. 20, carbon-hydrogen ratio 72, 77
  - No. 21, carbon-hydrogen ratio of 72, 77
    - smoke test of 58
- Wind, effect of, on efficiency 72* 167–168
- Wyoming coal, smoke test of 57
  - No. 2 B, clinker in 34
    - carbon-hydrogen ratio of 72, 78
    - smoke test of 58
  - No. 3, carbon-hydrogen ratio 72, 78
    - smoke test of 58

CLASSIFICATION OF THE PUBLICATIONS OF THE UNITED STATES GEOLOGICAL SURVEY.

[Bulletin No. 325.]

The publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of United States—folios and separate sheets thereof, (8) Geologic Atlas of United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists can be had on application.

Most of the above publications can be obtained or consulted in the following ways:

1. A limited number are delivered to the Director of the Survey, from whom they can be obtained, free of charge (except classes 2, 7, and 8), on application.
2. A certain number are delivered to Senators and Representatives in Congress or distribution.
3. Other copies are deposited with the Superintendent of Documents, Washington, D. C., from whom they can be had at prices slightly above cost.
4. Copies of all Government publications are furnished to the principal public libraries in the large cities throughout the United States, where they can be consulted by those interested.

The Professional Papers, Bulletins, and Water-Supply Papers treat of a variety of subjects, and the total number issued is large. They have therefore been classified into the following series: A, Economic geology; B, Descriptive geology; C, Systematic geology and paleontology; D, Petrography and mineralogy; E, Chemistry and physics; F, Geography; G, Miscellaneous; H, Forestry; I, Irrigation; J, Water storage; K, Pumping water; L, Quality of water; M, General hydrographic investigations; N, Water power; O, Underground waters; P, Hydrographic progress reports, Q, Fuels; R, Structural materials. This paper is the fifty-third in Series E, and the fifth in Series Q, the complete lists of which follow (PP=Professional Paper; B=Bulletin):

SERIES E, CHEMISTRY AND PHYSICS.

B 9. Report of work done in the Washington laboratory during the fiscal year 1883–84, by F. W. Clarke and T. M. Chatard. 1884. 40 pp. (Out of stock.)

B 14. Electrical and magnetic properties of the iron carburets, by Carl Barus and Vincent Strouhal. 1885. 238 pp. (Out of stock.)

B 27. Report of work done in the Division of Chemistry and Physics, mainly during the year 1884–85. 1886. 80 pp.

B 32. Lists and analyses of the mineral springs of the United States (a preliminary study), by Albert C. Peale. 1886. 235 pp. (Out of stock.)

B 35. Physical properties of the iron carburets, by Carl Barus and Vencent Strouhal. 1886. 62 pp.

B 36. Subsidence of fine solid particles in liquids, by Carl Barus. 1886. 58 pp. (Out of stock.)

B 42. Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1885–86, by F. W. Clarke. 1887. 152 pp., 1 pl. (Out of stock.)

B 47. Analyses of waters of the Yellowstone National Park, with an account of the methods of analyses employed, by F. A. Gooch and J. E. Whitfield. 1888. 84 pp. (Out of stock.)

B 52. Subaerial decay of rocks and origin of the red color of certain formations, by I. C. Russell. 1889. 65 pp., 5 pls. (Out of stock.)

B 54. On the thermoelectric measurement of high temperatures, by Carl Barus. 1889. 313 pp., 11 pls. (Out of stock.)

B 55. Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1886–87, by F. W. Clarke. 1889. 96 pp. (Out of stock.)

B 60. Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1887-88. 1890. 174 pp. (Out of stock.)
B 64. Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1888-89, by F. W. Clarke. 1890. 60 pp.
B 68. Earthquakes in California in 1889, by J. E. Keeler. 1890. 25 pp.
B 73. The viscosity of solids, by Carl Barus. 1891. xii, 139 pp., 6 pls.
B 78. Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1889-90, by F. W. Clarke. 1891. 131 pp. (Out of stock.)
B 90. Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1890-91, by F. W. Clarke. 1892. 77 pp.
B 92. The compressibility of liquids, by Carl Barus. 1892. 96 pp., 29 pls.
B 94. The mechanism of solid viscosity, by Carl Barus. 1892. 138 pp.
B 95. Earthquakes in California in 1890 and 1891, by E. S. Holden. 1892. 31 pp.
B 96. The volume thermodynamics of liquids, by Carl Barus. 1892. 100 pp.
B 103. High temperature work in igneous fusion and ebullition, chiefly in relation to pressure, by Carl Barus. 1893. 57 pp., 9 pls.
B 112. Earthquakes in California in 1892, by C. D. Perrine. 1893. 57 pp.
B 113. Report of work done in the Division of Chemistry and Physics during the fiscal years 1891-92 and 1892-93, by F. W. Clarke. 1893. 115 pp.
B 114. Earthquakes in California in 1893, by C. D. Perrine. 1894. 23 pp.
B 125. The constitution of the silicates, by F. W. Clarke. 1895. 100 pp. (Out of stock.)
B 129. Earthquakes in California in 1894, by C. D. Perrine. 1895. 25 pp.
B 147. Earthquakes in California in 1895, by C. D. Perrine. 1896. 23 pp.
B 148. Analyses of rocks, with a chapter on analytical methods, laboratory of the United States Geological Survey, 1880 to 1896, by F. W. Clarke and W. F. Hillebrand. 1897. 306 pp. (Out of stock.)
B 155. Earthquakes in California in 1896 and 1897, by C. D. Perrine. 1898. 47 pp.
B 161. Earthquakes in California in 1898, by C. D. Perrine. 1899. 31 pp., 1 pl.
B 167. Contributions to chemistry and mineralogy from the laboratory of the United States Geological Survey; F. W. Clarke, Chief Chemist. 1900. 166 pp.
B 168. Analyses of rocks, laboratory of the United States Geological Survey, 1880 to 1899, tabulated by F. W. Clarke. 1900. 308 pp. (Out of stock.)
B 176. Some principles and methods of rock analysis, by W. F. Hillebrand. 1900. 114 pp. (Out of stock.)
B 186. On pyrite and marcasite, by H. N. Stokes. 1900. 50 pp.
B 207. The action of ammonium chloride upon silicates, by F. W. Clarke and George Steiger. 1902 57 pp. (Out of stock.)
PP 14. Chemical analyses of igneous rocks published from 1884 to 1900, with a critical discussion of the character and use of analyses, by H. S. Washington. 1903. 495 pp.
PP 18. Chemical composition of igneous rocks expressed by means of diagrams, with reference to rock classification on a quantitative chemico-mineralogical basis, by J. P. Iddings. 1903. 98 pp., 8 pls.
B 220. Mineral analyses from the laboratories of the United States Geological Survey, 1880 to 1903, tabulated by F. W. Clarke, Chief Chemist. 1903. 119 pp.
B 228 Analyses of rocks from the laboratory of the United States Geological Survey, 1880 to 1903, tabulated by F. W. Clarke, Chief Chemist. 1904. 375 pp.
PP 28. The superior analyses of igneous rocks from Roth's tabellen, 1869 to 1884, arranged according to the quantitative system of classification, by H. S. Washington. 1904. 68 pp.
B 239. Rock cleavage, by C. K. Leith. 1904. 216 pp., 27 pls.
B 241. Experiments on schistosity and slaty cleavage, by G. F. Becker. 1904. 34 pp., 7 pls.
B 253. Comparison of a wet and crucible-fire method for the assay of gold telluride ores, with notes on the errors occurring in the operations of fire assay and parting, by W. F. Hillebrand and E. T. Allen. 1905. 33 pp.
B 261. Preliminary report of the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1905. 172 pp.
B 262. Contributions to mineralogy from the United States Geological Survey, by F. W. Clarke, W. F. Hillebrand, F. G. Ransome, S. L. Penfield, Waldemar Lindgren, George Steiger, and W. T. Schaller. 1905. 147 pp.
PP 48. Report on the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1906. 3 parts. 1,492 pp., 13 pls.
B 290. Preliminary report on the operations of the fuel-testing plant of the United States Geological Survey at St. Louis, Mo., 1905, by J. A. Holmes. 1906. 240 pp.
B 305. The analysis of silicate and carbonate rocks, by W. F. Hillebrand. 1906. 200 pp.
B 312. The interaction between minerals and water solutions, with special reference to geologic phenomena, by E. C. Sullivan. 1907. 69 pp.

B 316. Contributions to economic geology, 1906, Part II: Coal, lignite, and peat; M. R. Campbell geologist in charge. 1907. — pp., 23 pls.

B 323. Experimental work conducted in the chemical laboratory of the United States fuel-testing plant at St. Louis, Mo., January 1, 1905, to July 31, 1906, by N. W. Lord. 1907. 49 pp.

B 325. A study of four hundred steaming tests made at the fuel-testing plant, St. Louis, Mo., in 1904, 1905, and 1906, by L. P. Breckenridge, 1907. 196 pp.

SERIES Q, FUELS.

B 261. Preliminary report of the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1905. 172 pp.

PP 48. Report on the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1906. 3 parts. 1,492 pp., 13 pls.

B 290. Preliminary report on the operations of the fuel-testing plant of the United States Geological Survey at St. Louis, Mo., 1905, by J. A. Holmes. 1906. 240 pp.

B 323. Experimental work conducted in the chemical laboratory of the United States fuel-testing plant at St. Louis, Mo., January 1, 1905, to July 31, 1906, by N. W. Lord. 1907. 49 pp.

B 325. A study of four hundred steaming tests made at the fuel-testing plant, St. Louis, Mo., in 1904, 1905, and 1906, by L. P. Breckenridge, 1907. 196 pp.

Correspondence should be addressed to

THE DIRECTOR,
UNITED STATES GEOLOGICAL SURVEY,
WASHINGTON, D. C.

OCTOBER, 1907.

O

Bulletin No. 326

Series { A, Economic Geology, 104
B, Descriptive Geology, 128 }

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, DIRECTOR

THE ARKANSAS COAL FIELD

By ARTHUR J. COLLIER

WITH

REPORTS ON THE PALEONTOLOGY

By DAVID WHITE and G. H. GIRTY

WASHINGTON
GOVERNMENT PRINTING OFFICE
1907

CONTENTS.

Page.

- duction ... 1
- eed of investigation ... 1
- ersonnel ... 1
- tinerary ... 2
- cknowledgments ... 2
- eneral conclusions ... 4
- aphy ... 4
- osition and extent of the coal field ... 4
- aps of the coal field ... 5
- ommercial relations ... 7
- owns and villages ... 8
- rainage ... 8
- opographic provinces ... 9
- ral geology ... 10
- tratigraphy ... 10
  - General description and correlation ... 10
  - Atoka formation ... 13
  - Hartshorne sandstone ... 15
  - Spadra shale ... 17
  - Fort Smith formation ... 18
  - Paris shale ... 20
  - Savanna formation ... 21
  - Surficial deposits ... 22
- aleontology ... 23
  - Conclusions drawn from studies of the fossils ... 23
  - Report on fossil plants, by David White ... 24
    - Extent and character of the collections ... 24
    - Flora of the Coal Hill coal ... 25
    - Flora of the Spadra coal ... 26
    - Flora of the Coal Ridge or Charleston coal ... 27
    - The Paris flora ... 28
    - Lots of doubtful age ... 28
    - The Van Buren flora ... 30
    - Other collections ... 31
  - Report on marine Carboniferous fossils from the coal field of Arkansas, by George H. Girty ... 31
- tructure ... 35
  - General features ... 35
  - Anticlines ... 36
    - Backbone anticline ... 37
    - Biswell Hill anticline ... 37
    - Massard Prairie anticline ... 38
    - Montreal anticline ... 38
    - Hartford anticline ... 38

General geology—Continued.
Structure—Continued.
Anticlines—Continued.

Page.

- Mill Creek Ridge anticline 38
- Game Hill anticline 38
- Prairie View anticline 38
- Coal Hill anticline 39
- Russellville anticline 39

Synclines 39

- Fort Smith syncline 39
- Central syncline 39
- Greenwood syncline 39
- Sugarloaf syncline 39
- Poteau syncline 39
- Paris syncline 40
- Prairie View syncline 40
- Cabin Creek syncline 40
- London basin 40
- Ouita and Shinn basins 40

Faults 40

- General types 40
- Backbone Ridge fault 41
- Devils Backbone and Pine Ridge faults 42
- Caulksville fault 42
- Prairie View fault 42
- Clarksville fault 42
- Big Danger fault 43
- Spadra fault 44
- Hartman fault 44
- Coal Hill fault 45
- Altus fault 45
- Mill Creek fault 45
- Massard fault 46
- Mulberry fault 46

Minor structural features 47

- Joints 47
- Miniature folds 48

Economic geology 49

- The coal beds 49
  - Distribution 49
  - Coals of the Hartshorne horizon 50
    - Character and distribution 50
    - Bonanza and Jenny Lind district 51
    - Greenwood and Huntington district 56
      - Location and extent 56
      - Character and thickness of the coal 56
      - Hackett region 57
      - Greenwood region 59
      - Montreal, Burma, and Midland regions 60
      - Huntington region 61
      - Depths to the coal 62
    - Bates and Coaldale district 62
    - Charleston and Paris district 63
    - Van Buren and Alma district 65
    - *Coal Hill* and Denning district 66

Economic geology—Continued.
    The coal beds—Continued.
        Coals of the Hartshorne horizon—Continued.

Page.
- Spadra district 68
- Prairie View district 72
- Russellville district 74
    - Ouita basin 74
    - Shinn basin 75
- Philpott district 75
- Other localities 76

Coals of the Coal Ridge or Charleston horizon 77
- Charleston district 77
- Bonanza and Jenny Lind district 78
- Van Buren and Alma district 79
- Huntington district 79
- Paris district 79
- Spadra district 80
- Philpott district 80

Coals of the Paris horizon 80

Coals in the Atoka formation 81

Character of the coal 83
- Physical characteristics 83
- Classification of the coal 84
- Efficiency of the coal 86

Special tests and analyses 87
- Analyses made by Arkansas Geological Survey 87
- Fuel-testing plant samples 88
- Chemical analyses 95
- Coking tests 99
- Briquetting tests 100
- Boiler tests 101

Conditions of mining and development 103
- Production 103
- Methods of mining 105
    - System of working coal 105
    - Mining 105
    - Haulage, ventilation, and drainage 106
    - Minimum limit of thickness 106
- Preparation of the coal for market 106
- Labor 107
- Portion of contract between miners and operators 107

Mines, openings, and exposures of coal 112

Index 151

ILLUSTRATIONS.

Page.
PLATE I. Generalized columnar section of the coal-bearing rocks 12
II. *A*, View of Potato Hill; *B*, Exposure of Hartshorne sandstone south of Shinn basin 16
III. *A*, Exposure of the Hartshorne sandstone near Piney Creek, east of Knoxville; *B*, Apparent unconformity in Hartshorne sandstone due to false bedding 18

ILLUSTRATIONS.

Page.
IV. *A*, Jointing of sandstone in quarry at Cabin Creek; *B*, Irregular bedding in sandstone of Atoka or Winslow formation, one-half mile west of Ozark 20
V. Breaker at Scranton Anthracite Coal Company's mine, Spadra district 106
VI. Geologic and economic map and sections of the Arkansas coal field .... In pocket.

1. Map showing geographic position and railroad connection of the Arkansas coal field 5
2. Outline map of Arkansas coal field, showing mining centers, railroads, settlements, etc 6
3. Graphic sections of upper part of Atoka formation 14
4. Graphic sections of Hartshorne formation 16
5. Graphic sections of Spadra shale 18
6. Graphic sections of Fort Smith formation 20
7. Graphic sections of Paris shale 21
8. Map showing structural features of Arkansas coal field 36
9. Diagram of Backbone Ridge fault 41
10. Diagram of Clarksville fault 43
11. Minor structural features of coal beds 48
12. Distribution of Hartshorne coal horizon 51
13. Diagram showing relation of topography to geologic structure at Long Prairie, near Jenny Lind 52
14. Diagram showing relation of topography to geologic structure at Massard Prairie 52
15. Profile of coal bed at Jenny Lind 53
16. Graphic sections of coal along outcrop from Bonanza to Oak Grove.. 54
17. Graphic sections of coal on outcrop from Jenny Lind to Massard Prairie 55
18. Graphic sections of coal on outcrop from Hackett to Greenwood and Fidelity 58
19. Graphic sections of coal on outcrop in Montreal, Burma, and Midland regions 60
20. Graphic sections of coal on outcrop from Huntington through Hartford to Chasteen slope 61
21. Characteristic sections of coal bed on outcrop south of Poteau Mountain 63
22. Map showing structure of Coal Hill–Denning district 67
23. Graphic sections of coal at Denning 68
24. Map of Spadra and Prairie View coal fields 69
25. Sections showing thickness of coal bed in Spadra district, and in undeveloped field north of Lamar 71
26. Graphic sections of coal in Prairie View field 73
27. Characteristic sections of coal bed at Charleston horizon 77
28. Diagram showing composition of coals from different parts of the Arkansas field 85
29. Diagram showing relative calorific values of coals from different parts of the Arkansas field 87

THE ARKANSAS COAL FIELD.

By Arthur J. Collier.

INTRODUCTION.

Need of investigation.—Both the Carboniferous and the Tertiary rocks of Arkansas contain extensive deposits of coal, but only those of the older system in a field situated within the valley of Arkansas River and adjacent to the western boundary of the State have been exploited and are known to the trade. These coals have always borne a high reputation, but the demand for them has greatly increased in recent years. They grade from bituminous to semi-anthracite, and comparative experiments at the Geological Survey's fuel-testing plant have shown that coals of as good quality are not found elsewhere in the United States west of West Virginia.[a] New uses for them have been found which indicate their importance in the commercial development of the Middle West. At the same time mining operations within the field have demonstrated that its structure is more complex and the known areas of workable coal more limited than the results of earlier surveys would indicate.

For these reasons a number of operators and dealers in Arkansas coal called on the United States Geological Survey for more definite information regarding the extent and geologic structure of these coal beds, and in compliance with this demand a detailed reconnaissance investigation of the field was made from March 1 to August 1, 1906, the results of which are embodied in this report.

Personnel.—In both the field and the office the writer was efficiently assisted by Mr. Carl D. Smith, who was already familiar with the problems involved, through his previous connection with the survey of adjacent coal fields in Indian Territory, and who was identified with this investigation throughout both the field and the office work; by Mr. Sidney Paige, who participated in the field work during the first two months of the season, before his departure for Alaska, and after his return assisted in preparing some of the maps; and by Mr. R. D. Mesler, who brought to this work an

---

[a] Campbell, M. R., Classification of coals, in Report on the operations of the coal-testing plant 1904, Prof. Paper U. S. Geol. Survey No. 48, 1906, pp. 156–173.

Page.
PLATE IV. *A*, Jointing of sandstone in quarry at Cabin Creek; *B*, Irregular bedding in sandstone of Atoka or Winslow formation, one-half mile west of Ozark 20
V. Breaker at Scranton Anthracite Coal Company's mine, Spadra district 106
VI. Geologic and economic map and sections of the Arkansas coal field .... In pocket.

FIG. 1. Map showing geographic position and railroad connection of the Arkansas coal field 5
2. Outline map of Arkansas coal field, showing mining centers, railroads, settlements, etc 6
3. Graphic sections of upper part of Atoka formation 14
4. Graphic sections of Hartshorne formation 16
5. Graphic sections of Spadra shale 18
6. Graphic sections of Fort Smith formation 20
7. Graphic sections of Paris shale 21
8. Map showing structural features of Arkansas coal field 36
9. Diagram of Backbone Ridge fault 41
10. Diagram of Clarksville fault 43
11. Minor structural features of coal beds 48
12. Distribution of Hartshorne coal horizon 51
13. Diagram showing relation of topography to geologic structure at Long Prairie, near Jenny Lind 52
14. Diagram showing relation of topography to geologic structure at Massard Prairie 52
15. Profile of coal bed at Jenny Lind 53
16. Graphic sections of coal along outcrop from Bonanza to Oak Grove.. 54
17. Graphic sections of coal on outcrop from Jenny Lind to Massard Prairie 55
18. Graphic sections of coal on outcrop from Hackett to Greenwood and Fidelity 58
19. Graphic sections of coal on outcrop in Montreal, Burma, and Midland regions 60
20. Graphic sections of coal on outcrop from Huntington through Hartford to Chasteen slope 61
21. Characteristic sections of coal bed on outcrop south of Poteau Mountain 63
22. Map showing structure of Coal Hill–Denning district 67
23. Graphic sections of coal at Denning 68
24. Map of Spadra and Prairie View coal fields 69
25. Sections showing thickness of coal bed in Spadra district, and in undeveloped field north of Lamar 71
26. Graphic sections of coal in Prairie View field 73
27. Characteristic sections of coal bed at Charleston horizon 77
28. Diagram showing composition of coals from different parts of the Arkansas field 85
29. Diagram showing relative calorific values of coals from different parts of the Arkansas field 87

THE ARKANSAS COAL FIELD.

By Arthur J. Collier.

INTRODUCTION.

Need of investigation.—Both the Carboniferous and the Tertiary rocks of Arkansas contain extensive deposits of coal, but only those of the older system in a field situated within the valley of Arkansas River and adjacent to the western boundary of the State have been exploited and are known to the trade. These coals have always borne a high reputation, but the demand for them has greatly increased in recent years. They grade from bituminous to semianthracite, and comparative experiments at the Geological Survey's fuel-testing plant have shown that coals of as good quality are not found elsewhere in the United States west of West Virginia.[a] New uses for them have been found which indicate their importance in the commercial development of the Middle West. At the same time mining operations within the field have demonstrated that its structure is more complex and the known areas of workable coal more limited than the results of earlier surveys would indicate.

For these reasons a number of operators and dealers in Arkansas coal called on the United States Geological Survey for more definite information regarding the extent and geologic structure of these coal beds, and in compliance with this demand a detailed reconnaissance investigation of the field was made from March 1 to August 1, 1906, the results of which are embodied in this report.

Personnel.—In both the field and the office the writer was efficiently assisted by Mr. Carl D. Smith, who was already familiar with the problems involved, through his previous connection with the survey of adjacent coal fields in Indian Territory, and who was identified with this investigation throughout both the field and the office work; by Mr. Sidney Paige, who participated in the field work during the first two months of the season, before his departure for Alaska, and after his return assisted in preparing some of the maps; and by Mr. R. D. Mesler, who brought to this work an

---

[a] Campbell, M. R., Classification of coals, in Report on the operations of the coal-testing plant, 1904: Prof. Paper U. S. Geol. Survey No. 48, 1906, pp. 156-173.

Page.
PLATE IV. *A*, Jointing of sandstone in quarry at Cabin Creek; *B*, Irregular bedding in sandstone of Atoka or Winslow formation, one-half mile west of Ozark 20
V. Breaker at Scranton Anthracite Coal Company's mine, Spadra district 106
VI. Geologic and economic map and sections of the Arkansas coal field .... In pocket.

FIG. 1. Map showing geographic position and railroad connection of the Arkansas coal field 5
2. Outline map of Arkansas coal field, showing mining centers, railroads, settlements, etc 6
3. Graphic sections of upper part of Atoka formation 14
4. Graphic sections of Hartshorne formation 16
5. Graphic sections of Spadra shale 18
6. Graphic sections of Fort Smith formation 20
7. Graphic sections of Paris shale 21
8. Map showing structural features of Arkansas coal field 36
9. Diagram of Backbone Ridge fault 41
10. Diagram of Clarksville fault 43
11. Minor structural features of coal beds 48
12. Distribution of Hartshorne coal horizon 51
13. Diagram showing relation of topography to geologic structure at Long Prairie, near Jenny Lind 52
14. Diagram showing relation of topography to geologic structure at Massard Prairie 52
15. Profile of coal bed at Jenny Lind 53
16. Graphic sections of coal along outcrop from Bonanza to Oak Grove .. 54
17. Graphic sections of coal on outcrop from Jenny Lind to Massard Prairie 55
18. Graphic sections of coal on outcrop from Hackett to Greenwood and Fidelity 58
19. Graphic sections of coal on outcrop in Montreal, Burma, and Midland regions 60
20. Graphic sections of coal on outcrop from Huntington through Hartford to Chasteen slope 61
21. Characteristic sections of coal bed on outcrop south of Poteau Mountain 63
22. Map showing structure of Coal Hill–Denning district 67
23. Graphic sections of coal at Denning 68
24. Map of Spadra and Prairie View coal fields 69
25. Sections showing thickness of coal bed in Spadra district, and in undeveloped field north of Lamar 71
26. Graphic sections of coal in Prairie View field 73
27. Characteristic sections of coal bed at Charleston horizon 77
28. Diagram showing composition of coals from different parts of the Arkansas field 85
29. Diagram showing relative calorific values of coals from different parts of the Arkansas field 87

THE ARKANSAS COAL FIELD.

By Arthur J. Collier.

INTRODUCTION.

Need of investigation.—Both the Carboniferous and the Tertiary rocks of Arkansas contain extensive deposits of coal, but only those of the older system in a field situated within the valley of Arkansas River and adjacent to the western boundary of the State have been exploited and are known to the trade. These coals have always borne a high reputation, but the demand for them has greatly increased in recent years. They grade from bituminous to semianthracite, and comparative experiments at the Geological Survey's fuel-testing plant have shown that coals of as good quality are not found elsewhere in the United States west of West Virginia.[a] New uses for them have been found which indicate their importance in the commercial development of the Middle West. At the same time mining operations within the field have demonstrated that its structure is more complex and the known areas of workable coal more limited than the results of earlier surveys would indicate.

For these reasons a number of operators and dealers in Arkansas coal called on the United States Geological Survey for more definite information regarding the extent and geologic structure of these coal beds, and in compliance with this demand a detailed reconnaissance investigation of the field was made from March 1 to August 1, 1906, the results of which are embodied in this report.

Personnel.—In both the field and the office the writer was efficiently assisted by Mr. Carl D. Smith, who was already familiar with the problems involved, through his previous connection with the survey of adjacent coal fields in Indian Territory, and who was identified with this investigation throughout both the field and the office work; by Mr. Sidney Paige, who participated in the field work during the first two months of the season, before his departure for Alaska, and after his return assisted in preparing some of the maps; and by Mr. R. D. Mesler, who brought to this work an

---

[a] Campbell, M. R., Classification of coals, in Report on the operations of the coal-testing plant, 1904: Prof. Paper U. S. Geol. Survey No. 48, 1906, pp. 156-173.

Page.
PLATE IV. *A*, Jointing of sandstone in quarry at Cabin Creek; *B*, Irregular bedding in sandstone of Atoka or Winslow formation, one-half mile west of Ozark 20
V. Breaker at Scranton Anthracite Coal Company's mine, Spadra district 106
VI. Geologic and economic map and sections of the Arkansas coal field .... In pocket.

FIG. 1. Map showing geographic position and railroad connection of the Arkansas coal field 5
2. Outline map of Arkansas coal field, showing mining centers, railroads, settlements, etc 6
3. Graphic sections of upper part of Atoka formation 14
4. Graphic sections of Hartshorne formation 16
5. Graphic sections of Spadra shale 18
6. Graphic sections of Fort Smith formation 20
7. Graphic sections of Paris shale 21
8. Map showing structural features of Arkansas coal field 36
9. Diagram of Backbone Ridge fault 41
10. Diagram of Clarksville fault 43
11. Minor structural features of coal beds 48
12. Distribution of Hartshorne coal horizon 51
13. Diagram showing relation of topography to geologic structure at Long Prairie, near Jenny Lind 52
14. Diagram showing relation of topography to geologic structure at Massard Prairie 52
15. Profile of coal bed at Jenny Lind 53
16. Graphic sections of coal along outcrop from Bonanza to Oak Grove 54
17. Graphic sections of coal on outcrop from Jenny Lind to Massard Prairie 55
18. Graphic sections of coal on outcrop from Hackett to Greenwood and Fidelity 58
19. Graphic sections of coal on outcrop in Montreal, Burma, and Midland regions 60
20. Graphic sections of coal on outcrop from Huntington through Hartford to Chasteen slope 61
21. Characteristic sections of coal bed on outcrop south of Poteau Mountain 63
22. Map showing structure of Coal Hill–Denning district 67
23. Graphic sections of coal at Denning 68
24. Map of Spadra and Prairie View coal fields 69
25. Sections showing thickness of coal bed in Spadra district, and in undeveloped field north of Lamar 71
26. Graphic sections of coal in Prairie View field 73
27. Characteristic sections of coal bed at Charleston horizon 77
28. Diagram showing composition of coals from different parts of the Arkansas field 85
29. Diagram showing relative calorific values of coals from different parts of the Arkansas field 87

THE ARKANSAS COAL FIELD.

By Arthur J. Collier.

INTRODUCTION.

Need of investigation.—Both the Carboniferous and the Tertiary rocks of Arkansas contain extensive deposits of coal, but only those of the older system in a field situated within the valley of Arkansas River and adjacent to the western boundary of the State have been exploited and are known to the trade. These coals have always borne a high reputation, but the demand for them has greatly increased in recent years. They grade from bituminous to semianthracite, and comparative experiments at the Geological Survey's fuel-testing plant have shown that coals of as good quality are not found elsewhere in the United States west of West Virginia.[a] New uses for them have been found which indicate their importance in the commercial development of the Middle West. At the same time mining operations within the field have demonstrated that its structure is more complex and the known areas of workable coal more limited than the results of earlier surveys would indicate.

For these reasons a number of operators and dealers in Arkansas coal called on the United States Geological Survey for more definite information regarding the extent and geologic structure of these coal beds, and in compliance with this demand a detailed reconnaissance investigation of the field was made from March 1 to August 1, 1906, the results of which are embodied in this report.

Personnel.—In both the field and the office the writer was efficiently assisted by Mr. Carl D. Smith, who was already familiar with the problems involved, through his previous connection with the survey of adjacent coal fields in Indian Territory, and who was identified with this investigation throughout both the field and the office work; by Mr. Sidney Paige, who participated in the field work during the first two months of the season, before his departure for Alaska, and after his return assisted in preparing some of the maps; and by Mr. R. D. Mesler, who brought to this work an

---

[a] Campbell, M. R., Classification of coals, in Report on the operations of the coal-testing plant, 1904: Prof. Paper U. S. Geol. Survey No. 48, 1906, pp. 156-173.

Page.
PLATE IV. *A*, Jointing of sandstone in quarry at Cabin Creek; *B*, Irregular bedding in sandstone of Atoka or Winslow formation, one-half mile west of Ozark 20
V. Breaker at Scranton Anthracite Coal Company's mine, Spadra district 106
VI. Geologic and economic map and sections of the Arkansas coal field .... In pocket.

FIG. 1. Map showing geographic position and railroad connection of the Arkansas coal field 5
2. Outline map of Arkansas coal field, showing mining centers, railroads, settlements, etc 6
3. Graphic sections of upper part of Atoka formation 14
4. Graphic sections of Hartshorne formation 16
5. Graphic sections of Spadra shale 18
6. Graphic sections of Fort Smith formation 20
7. Graphic sections of Paris shale 21
8. Map showing structural features of Arkansas coal field 36
9. Diagram of Backbone Ridge fault 41
10. Diagram of Clarksville fault 43
11. Minor structural features of coal beds 48
12. Distribution of Hartshorne coal horizon 51
13. Diagram showing relation of topography to geologic structure at Long Prairie, near Jenny Lind 52
14. Diagram showing relation of topography to geologic structure at Massard Prairie 52
15. Profile of coal bed at Jenny Lind 53
16. Graphic sections of coal along outcrop from Bonanza to Oak Grove.. 54
17. Graphic sections of coal on outcrop from Jenny Lind to Massard Prairie 55
18. Graphic sections of coal on outcrop from Hackett to Greenwood and Fidelity 58
19. Graphic sections of coal on outcrop in Montreal, Burma, and Midland regions 60
20. Graphic sections of coal on outcrop from Huntington through Hartford to Chasteen slope 61
21. Characteristic sections of coal bed on outcrop south of Poteau Mountain 63
22. Map showing structure of Coal Hill–Denning district 67
23. Graphic sections of coal at Denning 68
24. Map of Spadra and Prairie View coal fields 69
25. Sections showing thickness of coal bed in Spadra district, and in undeveloped field north of Lamar 71
26. Graphic sections of coal in Prairie View field 73
27. Characteristic sections of coal bed at Charleston horizon 77
28. Diagram showing composition of coals from different parts of the Arkansas field 85
29. Diagram showing relative calorific values of coals from different parts of the Arkansas field 87

THE ARKANSAS COAL FIELD.

By Arthur J. Collier.

INTRODUCTION.

Need of investigation.—Both the Carboniferous and the Tertiary rocks of Arkansas contain extensive deposits of coal, but only those of the older system in a field situated within the valley of Arkansas River and adjacent to the western boundary of the State have been exploited and are known to the trade. These coals have always borne a high reputation, but the demand for them has greatly increased in recent years. They grade from bituminous to semianthracite, and comparative experiments at the Geological Survey's fuel-testing plant have shown that coals of as good quality are not found elsewhere in the United States west of West Virginia.[a] New uses for them have been found which indicate their importance in the commercial development of the Middle West. At the same time mining operations within the field have demonstrated that its structure is more complex and the known areas of workable coal more limited than the results of earlier surveys would indicate.

For these reasons a number of operators and dealers in Arkansas coal called on the United States Geological Survey for more definite information regarding the extent and geologic structure of these coal beds, and in compliance with this demand a detailed reconnaissance investigation of the field was made from March 1 to August 1, 1906, the results of which are embodied in this report.

Personnel.—In both the field and the office the writer was efficiently assisted by Mr. Carl D. Smith, who was already familiar with the problems involved, through his previous connection with the survey of adjacent coal fields in Indian Territory, and who was identified with this investigation throughout both the field and the office work; by Mr. Sidney Paige, who participated in the field work during the first two months of the season, before his departure for Alaska, and after his return assisted in preparing some of the maps; and by Mr. R. D. Mesler, who brought to this work an experience gained in adjacent regions north and west, and remained with the party through two months of the field season. Much of the accuracy of this report is due to the faithful work of these geologists.

---

[a] Campbell, M. R., Classification of coals, in Report on the operations of the coal-testing plant, 1904: Prof. Paper U. S. Geol. Survey No. 48, 1906, pp. 156–173.

Mr. M. R. Campbell, geologist in charge of economic geology of fuels, spent two weeks with the party in the field, making many valuable suggestions and directing the course of the work. Prof. A. H. Purdue, of the University of Arkansas, author of the Winslow folio, also visited the party while in the northwestern part of the field and contributed valuable information regarding the details of the structure there, as indicated by his interpretation of the geology of the Winslow quadrangle.[a]

Itinerary.—The field party began work early in March, 1906, at Midland, Ark., and, after carrying the investigation eastward along the southern boundary of the coal field to its eastern extremity near Dardanelle, turned westward along the northern boundary and completed the greater part of the field work by the last of June. Mr. Smith, however, with a smaller outfit, remained in the field until the last of July, reviewing many doubtful points regarding which the interpretation had not been fully settled during the first examination. Although the underground workings of many of the mines were examined and the coal from them was sampled, investigations of that character were prevented during the latter part of the season by a general strike among the miners. All the mines were shut down, and the fans and often the pumps were stopped, making the workings inaccessible.

Acknowledgments.—In the course of this investigation full use has been made of the maps and reports concerning the region that have previously been issued by various geological organizations. The most complete report on this field was made by the Geological Survey of Arkansas, under the direction of Dr. J. C. Branner, and published in 1888.[b] This report contains a brief summary of the information obtained by the Arkansas Survey, and was published in advance of a more complete description of the field. Further information regarding the structure and geology of this part of Arkansas was subsequently published by Winslow.[c] Unfortunately, the final report of the Arkansas Survey on the coal field has never been published, and the manuscripts were not available. A very large and important part of the work of the State Survey in this region consisted in the preparation of detailed topographic maps on a scale of 1 mile to the inch, with contour intervals of 20 feet, but like the final coal report these maps were never issued to the public, though the plates were partially engraved by the United States Geological Survey. A small edition was printed from the partially engraved plates and used during the season of 1906 as a basis for field mapping, and, although often inaccurate in topographic detail and generally deficient in culture, they are, nevertheless, the most useful maps of this field yet prepared and were of great assistance in the geologic work.

---

[a] Purdue, A. H., Description of the Winslow quadrangle: Geologic Atlas U. S., folio —, U. S. Geol. Survey, 1907.

[b] Winslow, Arthur, Ann. Rept. Geol. Survey Arkansas, vol. 2, 1888.

[c] Winslow, Arthur, The geotectonic and physiographic geology of western Arkansas: Bull. Geol. Soc. America, vol. 2, 1891, pp. 275-287, pl. 8.

The results obtained and the conclusions reached in this paper have to a considerable extent been made possible by the careful detailed work which has been done by members of the United States Geological Survey in areas north and west of that under discussion. Acknowledgments for suggestions and information contained in published reports and for advice in the conduct of the field work are due to Mr. Joseph A. Taff,[a] who has for many years been identified with the work of the Survey in the adjacent coal fields of Indian Territory, and also to Prof. A. H. Purdue,[b] whose detailed and accurate geologic map of the Winslow quadrangle includes a portion of the northern part of this field.

Since the disorganization of the State Survey developments within the coal field have been very extensive. Many new openings on the coal have been made and much prospecting by drilling and other means has been done to determine the extent of the coal beds. The greater part of the information thus obtained was available and has been used in the preparation of this report. In the course of the field work many suggestions relative to the work were received from coal operators and prospectors, to whose cooperation much of the value of this report is due.

The various companies and individuals to whom the writer is more especially indebted for such information and assistance are as follows: The Western Coal and Mining Company of St. Louis, Mo., operating in the Jenny Lind and Denning districts, supplied the records of over 100 drill holes in various parts of the field. The Cherokee Construction Company of Fort Smith, Ark., operating mines near Midland and Hartford, a company that has done much intelligent prospecting in the western part of the field, permitted the examination of all their well records and mine maps. The Central Coal and Coke Company, operating at Bonanza and Huntington, who have accumulated much information regarding various parts of the field, supplied copies of their more important records. Mr. H. H. Jackman, manager of the Spadra Creek Coal Company of Spadra, furnished records of a number of characteristic well sections in various parts of the field. Mr. Harry Kelly, president of the Mansfield Gas Company of Fort Smith, who has supervised the drilling of many deep wells in the rocks below the coal measures, kindly permitted an examination of the records of 13 typical wells, each over 1,000 feet deep, near Mansfield and Fort Smith, and supplied data obtained from many years of intelligent study of local geology. Messrs. Martin Rafter, State mine inspector, of Coal Hill; Henry Strother, real estate agent, of Fort Smith; Fremont Stokes, of Clarksville, and many others contributed material aid in assembling information regarding the facts herewith presented, and mine operators in general throughout the field very courteously granted access to mine maps and provided every facility possible for the examination of the underground workings.

---

[a] Taff, Joseph A., and Adams, George I., Geology of the eastern Choctaw coal field: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 2, 1900, pp. 259–311.

Taff, Joseph A., Description of the Coalgate quadrangle: Geologic Atlas U. S., folio 74, 1901; also Description of the Atoka quadrangle, folio 79, 1902, U. S. Geol. Survey; The Southwestern coal field: Twenty-second Ann. Rept. U. S. Geol. Survey, pt. 3, 1902, pp. 361–413; maps of segregated coal lands in Indian Territory; U. S. Department of the Interior Circulars Nos. 1, 2, 3, 4, 5, and 6, 1904; Description of the Tahlequah quadrangle, folio 122, U. S. Geol. Survey, 1905. (Also Sallisaw and Windingstair folios, in preparation.)

[b] Purdue, A. H., Description of the Winslow quadrangle: Geologic Atlas U. S., folio —, U. S. Geol. Survey, 1907.

General conclusions.—It will be shown in the following pages that the areas known to contain workable coal are more limited than is generally supposed, but that several promising districts of considerable extent have not yet been prospected. The complexity of the geologic structure along the northern edge of the field is here indicated for the first time, and it is believed that considerable unnecessary expense in searching for coal in unfavorable localities may be avoided, or if such work is undertaken the chances of success or failure may be better understood by use of the information here presented.

GEOGRAPHY.

Position and extent of the coal field.—The coal field herein described is situated in the western part of the State of Arkansas, adjoining the Indian Territory line, from which it extends eastward for 75 miles. Its general geographic position is shown in fig. 1, and its outline and extent are shown in fig. 2. It is about 50 miles wide at its western end, but the belt containing workable coal contracts sharply 12 miles from the boundary, beyond which its average width is not more than 20 miles. The areas of workable coal are more or less irregularly distributed over the district above described and some of them are in detached basins not known to be connected with one another. This irregularity and subdivision of the field is due in part to a complex geologic structure and in part to the peculiarities and local variations in the coal beds themselves, making them unfit for mining in some parts of the field, although their presence there is well known. The productive areas of the east end of the field are north of and those of the west end are south of Arkansas River.

Since nearly all the workable coal beds occur in or above the horizon of the Hartshorne coal of Indian Territory, the limits of the *coal field* have been determined by the presence or absence of rocks overlying this horizon. (See fig. 2.) Coal beds that have been prospected at only a few localities also occur in some of the lower rocks, and their outcrops are found at considerable distances beyond the limits of the field as defined above. Most of these are probably not of commercial value but some of them may prove valuable locally, so that the extent of the coal fields will probably be increased by future discoveries.

Maps of the coal field.—This region was surveyed and subdivided into townships and sections of conventional size more than fifty years ago, but the maps made at that time show very few of the improvements now existing. The section and township corners established by these surveys were marked by the customary wooden posts and witness trees, but the original monuments have long ago rotted away or have been replaced by later ones established by local surveyors. At many places old fences and roads, placed on the lines when they were new, are the only evidences remaining to indicate their positions. These surveys were made with the needle compass, and the lines thus established often varied several degrees from true meridians and parallels. Nearly all the published maps

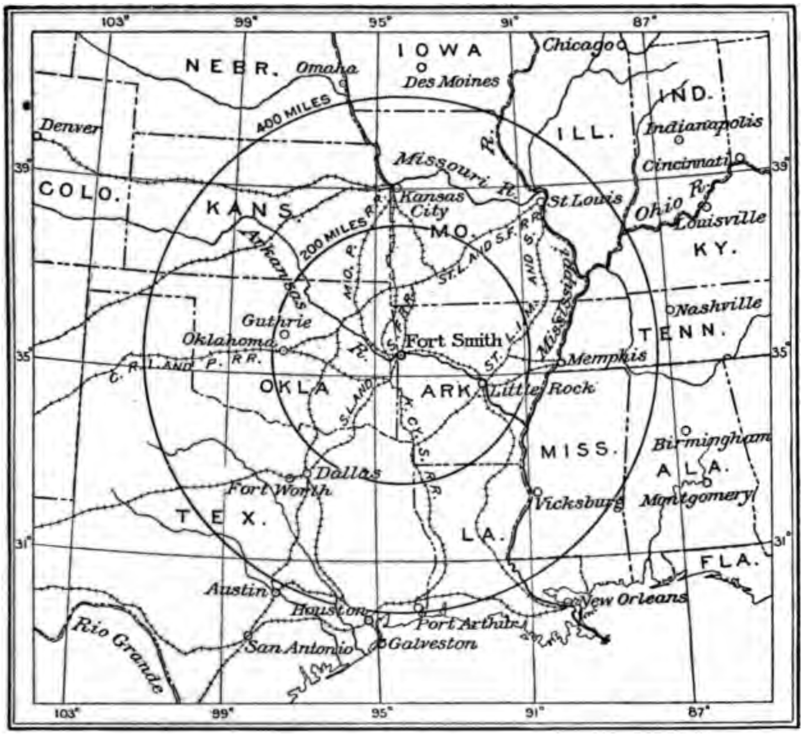


FIG. 1.—Map showing geographic position and railroad connection of the Arkansas coal field.

of Arkansas, however, are based on them and are sufficiently accurate for ordinary purposes.

The topographers of the United States Geological Survey made a reconnaissance of the field in 1888, the result of their work being topographic sheets of several thirty-minute quadrangles on a scale of one-half inch to the mile. Unfortunately, these maps were deficient both in topographic detail and in culture, a most notable defect being the omission of township and section lines, which are of the utmost economic value in any map to be used by the residents of the district. When the Arkansas Geological Survey undertook to interpret the geology of the coal field the existing maps were found to be inadequate, and they therefore conducted a topographic survey in connection with their geologic work, using the base presented by the Land Office maps for control. The topography was sketched by a number of assistants, who retraced the section lines and determined elevations by aneroid barometers. This work resulted in the preparation of a detailed topographic map on a scale of 1 inch to the mile, covering the whole of the coal field. Unfortunately, the State survey was discontinued before this map was completed and and it has never been published, though the engraving of the plates by the United States Geological Survey was nearly completed. In many respects it is the most complete map of the Arkansas coal field that has been prepared, and a small edition was printed and used in the field work on which this report is based. The map (Pl. VI)

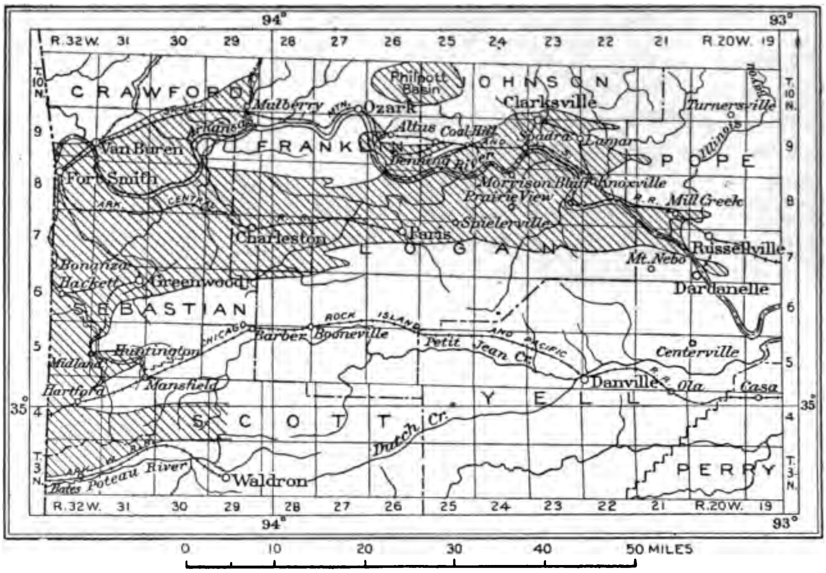


FIG. 2.—Outline map of Arkansas coal field, showing mining centers, railroads, settlements, etc.

herewith presented, however, is based on the United States Geological Survey sheets of the region with the addition of the township and section lines, the topography being omitted in order to insure more speedy publication. Although a contour map would be more desirable from a scientific point of view, it is thought that the map as prepared will be of nearly equal value to those who are interested in the development of the field. The geologic structure is complex, but the scale, one-half inch to the mile, is sufficiently large to show all that is known or can be learned at present, except in some small areas where there have been more extensive developments, the details of which are presented in various text figures.

Commercial relations.—Fort Smith, the center of the coal-mining industry, is the principal town in western Arkansas. Its population in 1900, as determined by the Twelfth Census, was 11,587; its present population is about 20,000. It is approximately 250 miles from Kansas City, 350 miles from St. Louis, and 400 miles from the Gulf of Mexico, with which it is connected by the lines of the St. Louis and San Francisco, the St. Louis, Iron Mountain and Southern, and the Kansas City Southern railway systems (see fig. 1, p. 5). Branch lines and independent railroads of less importance, which radiate from Fort Smith and afford transportation to the various coal-mining districts are as follows:

The Little Rock and Fort Smith branch of the Iron Mountain Railway extends through the whole length of the field, north of the river, with spurs and branch roads to the mines near Denning, Coal Hill, Spadra, and Russellville. South of the river the Arkansas Central Railroad extends from Fort Smith to Paris; a branch of the Iron Mountain Railway leads to Greenwood, with a spur to the mines at Jenny Lind; the Mansfield branch of the St. Louis and San Francisco system affords transportation to the mines at Bonanza, Hackett, Montreal, and Huntington and connects with the Choctaw (Chicago, Rock Island and Pacific) line from Memphis; the Midland Valley Railroad follows the outcrop of the coal from Hackett east to Greenwood and thence south past Montreal and Midland to Hartford, affording transportation to a large number of small mines; and the extreme southern part of the field is reached by the Waldron branch of the Kansas City Southern Railway.

With the development of the mining industry new railroads have been projected, and during the last season surveys were in progress for a line connecting Fort Smith with the undeveloped district near Prairie View, 10 miles east of Paris, in Logan County. A railroad is also in course of construction from Dardanelle southward across a district that lies outside of the coal field as at present recognized but contains prospects of coal, some of which will probably be developed into mines.

The coal field is well supplied with wagon roads, very few of which are in good condition in either winter or summer, though in many places, where they are located along the outcrops of ridge-making sandstones, the road bed is firm but rough. Nearly all the roads for a few miles out of Fort Smith are macadamized and dressed with crushed chert from the northern part of the State. They are in good good condition the year round and effectually demonstrate the practicability and value of such improvements. The cost of such roads is so great, however, that it will doubtless be many years before they are extended over the whole of this field.

Towns and villages.—Outside of Fort Smith the important towns are the county seats and the villages around the mines. The county seats are supported mainly by agricultural trade and most of them present a thrifty and attractive appearance. They are: Van Buren, Crawford County, population 2,573; Greenwood, Sebastian County, population 491; Ozark, Franklin County, population 848; Paris, Logan County, population 836; Clarksville, Johnson County, population, 1,086; Russellville, Pope County, population 1,832; and Dardanelle, Yell County, population 1,602.[a]

The more important coal-mining towns are Bonanza, population 906; Jenny Lind, population 425; Huntington, population 1,298; Hartford, population 460; Coal Hill, population 1,341; Denning, population 700; and Spadra, population 260.

Drainage.—The coal field is drained by Arkansas River and its tributaries. Arkansas River is the main waterway and extends through the whole length of the field. It rises in the Rocky Mountains about 400 miles northwest of this region and joins the Mississippi at the eastern boundary of the State, where it carries a large volume of water. Before the building of railroads it was the principal method of transportation in this part of the State, but it is very little used at present, no steamers having been seen on the river during the last field season. It flows over a wide bed filled with many sandbars and was probably never navigable during extremely low stages. The river bed is generally from 50 to 100 feet below the general lowland level of the region. Its banks are bordered by flood plains, at some places several miles wide, that are overflowed every few years, back of which there is in many localities a low escarpment rising to the general lowland plain.

Most of the tributaries of the Arkansas that enter the main stream from the south rise within the coal-bearing district and are always heavily charged with very fine sediment. Poteau River, one of the largest of these, is the source of water supply for Fort Smith, and although the water is said to be wholesome it is never clear. This river rises south of Poteau Mountain but within a short distance crosses the State line into Indian Territory, in which the major part of its course is located. It again reaches the State line near its mouth, which is in Arkansas. The other notable streams south of the river are Vache Grasse, Sixmile, Hurricane, and Shoal creeks, all of which are sluggish and muddy, like Poteau River.

---

[a] The population stated is that given by the Twelfth Census. Since 1900 the population of many of these towns has increased rapidly and that of some of them has probably more than doubled.

Nearly all the streams that enter Arkansas River from the north rise within the Boston Mountain area and are clear except at times of freshet. They carry larger volumes of water than the streams entering the river from the south. The more important northern tributaries of the Arkansas within the coal district are Lee Creek, Frog Bayou, Mulberry River, Horsehead, Spadra, and Piney creeks, and Illinois Bayou. None of these tributaries, except possibly a part of Poteau River, can be regarded as navigable.

Topographic provinces.—In this region three topographic provinces, the Boston Mountains, the Arkansas Valley, and the Ouachita Mountains, extending from Arkansas westward into Indian Territory, are recognized by geologists.

The Boston Mountains, which comprise the southern part of the Ozark Mountain region, consist of broad, flat-topped hills forming a dissected plateau whose highest point is about 2,000 feet above the sea.[a] In this region the strata are approximately horizontal; the flat-topped hills are capped by beds of hard sandstone, and the valleys, which are regarded as of comparatively recent origin, are deep and narrow. The southern edge of this mountain district in Arkansas is marked in many places by rather abrupt escarpments that rise from the lowlands of the valley to the lower plateau levels.

The Arkansas Valley province, comprising a belt about 50 miles wide, in which the coal fields are situated, lies south of the Boston Mountains, and is characterized by elevations averaging not more than 500 feet above the sea. Its more definite features are a base-level plain comprising a network of broad alluvial valleys surmounted by many ridges and flat-topped hills, most of whose summits blend in an even sky line about 650 to 700 feet above the sea. Where the strata are moderately inclined the topography is marked by many long, persistent, even-topped ridges, whose summits are from 50 to 100 feet above the base-level plain. A few of the hills take the form of low, broad domes mantled with hard sandstone, and at some places where the rocks are nearly horizontal there are buttes whose summits reach from 1,000 to 3,000 feet above tide, and from 400 to 2,000 feet above the general lowland. Notable among elevations of this character are Sugarloaf and Poteau mountains, near the western end of the coal field, and Magazine, Short, and Nebo mountains, near its eastern end. Magazine Mountain, with an elevation of 3,000 feet, is the highest eminence in Arkansas. Potato Hill, a cone-shaped butte of this type, is shown in Pl. II, *A*. All of these features are direct resultants of the erosion of diverse bed-rock structures, the long, narrow ridges indicating moderately inclined rocks, while the buttes (Pl. II, *A*) indicate horizontal rocks in synclinal basins, and the domes are short anticlines. As a general rule the ridges are more pronounced in the southern part of the field, while the topography of the northern part partakes more of the nature of that found in the Boston Mountains.

---

[a] Purdue, A. H., Physiography of the Boston Mountains, Arkansas: Jour. Geol., vol. 9, 1901, pp. 694-701. Hershey, O. H., Peneplain of the Ozark highland: Am. Geologist, vol. 27, 1901, pp. 25-41.

The Ouachita Mountain province, which lies south of Arkansas Valley, is characterized by many sharp ridges, produced by the erosion of steeply dipping beds striking approximately east and west.[a] These ridges rise to a nearly uniform height, suggesting an old base-level erosion plain which has been so unequally elevated that while it is over 2,000 feet above the sea at the Arkansas-Indian Territory boundary it declines to only about 500 feet at its eastern end near Hot Springs.[b] From this description it will be seen that Arkansas Valley, in which these coal fields lie, is situated between two mountain masses of very distinct types, and that its topography is to a considerable extent intermediate in character between the two.

GENERAL GEOLOGY.

STRATIGRAPHY.

GENERAL DESCRIPTION AND CORRELATION.

The Arkansas field comprises the eastern end of a large area of coal land which has its greatest extent in Indian Territory. The stratigraphic relations of the rocks of that part of the field which lies in Indian Territory have already been studied in detail and mapped by geologists of the Survey.[c] A part of the northern edge of the coal field in Arkansas has also been mapped, and the results of investigations made there have been submitted for publication.[d] The formations comprising the stratigraphic column in Arkansas are directly comparable to those of Indian Territory, and there is also a marked similarity in the general type of geologic structure in the two districts. The various rock formations as defined and named in Indian Territory will therefore be described as they occur in Arkansas.

---

[a] Griswold, L. S., Ann. Rept. Geol. Survey Arkansas for 1890, vol. 3, 1892, pp. 195-202.

[b] Ashley, G. H., Geology of the Paleozoic area of Arkansas south of the novaculite region: Proc. Am. Philos. Soc., vol. 36, 1897, pp. 217-318.

[c] Taff, Joseph A., and Adams, George I., Geology of the eastern Choctaw coal field: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 2, 1900, pp. 259-311.

Taff, Joseph A., Coalgate folio (No. 74), 1901, and Atoka folio (No. 79), 1902, U. S. Geol. Survey; The Southwestern coal field, Twenty-second Ann. Rept. U. S. Geol. Survey, pt. 3, 1902, pp. 361-413; Maps of segregated coal lands in Indian Territory, U. S. Department of the Interior Circulars Nos. 1, 2, 3, 4, 5, and 6, 1904; Tahlequah folio (No. 122), U. S. Geol. Survey, 1905. (Also Sallisaw and Windingstair folios, in preparation.)

[d] Purdue, A. H., Winslow folio (No. —), U. S. Geol. Survey, 1907.

All the rocks herein described belong to the middle Carboniferous or Pennsylvanian series. They present a rather monotonous sequence of sandstones and shales with little contrast between individual beds. Except for the coal beds themselves there are no members that can be identified with certainty by lithologic characters. Limestone beds, which are interspersed through the series in other fields and aid the geologist by serving as horizon markers, are here almost totally wanting. Moreover, there is much local variation in the character of the rocks, and especially in the sandstone lenses, and correlations from one part of the field to another that are based on lithologic similarity alone are of little value.

In the region north of the coal field, near Fayetteville, lower Carboniferous (Mississippian) shales, sandstones, and limestones are exposed, and farther south these are overlapped by about 1,500 feet of shales and sandstones called the Winslow formation. The Winslow extends to the edge of the coal field, and the upper bed of this formation, as described by Purdue, apparently forms the base of the coal-bearing rocks of Arkansas. In Indian Territory the basal bed of the coal-bearing strata is a thick, often massive, sandstone, named for the town of Hartshorne. This sandstone overlies several thousand feet of shale, with only occasional sandstone beds interspersed, which has been called the Atoka shale in the southern part of the coal field, but occupies a position equivalent to that of the Winslow formation in the northern part. It is therefore evident that the Pennsylvanian rocks below the coal-bearing beds rapidly increase in thickness toward the south.

The coal-bearing rocks in Indian Territory comprise several thousand feet of sandstone and shale, which has been divided as follows:

Coal-bearing rocks in Indian Territory.

	Feet.
Boggy shale	2,000
Savanna sandstone	1,000
McAlester shale	2,000
Hartshorne sandstone	200

The Hartshorne sandstone, at the base of the series, is a thin but very persistent formation, which has been traced for 150 miles across the southern edge of the Indian Territory field, but has not heretofore been identified at its northern edge. The McAlester shale, which overlies the Hartshorne sandstone, contains the Hartshorne and McAlester coals. A group of massive sandstones and interbedded shales, including the Witteville coal bed, make up the Savanna formation, which is overlain by the Boggy shale, also including one or two coal beds.

The coal-bearing rocks of Arkansas were separated by the Geological Survey of Arkansas into three divisions, as follows:[a]

Coal-bearing rocks in Arkansas, according to the Geological Survey of Arkansas.

	Feet.
Western and upper division, including Huntington and other coal beds..	3,000±
Intermediate barren division, a succession of shale and sandstone beds which, though variable in magnitude, have an aggregate thickness not less than.	500
Eastern and lower division, including the coal beds in Coal Hill, Spadra, Ouita, and Shinn basins......	250±

These divisions were not clearly defined, and the rocks below the coal-bearing formations were not discussed. The correlation of these groups into which the coal measures of Arkansas and Indian Territory have been subdivided by various surveys is set forth in the following table:

Stratigraphic relations in the Arkansas-Indian Territory coal field as exhibited in reports already published and in the present report.

Arkansas Survey preliminary report.	Indian Territory-southwestern Arkansas coal fields, J. A. Taff.[b]	Winslow folio, U. S. Geol. Survey, A. H. Purdue.	Arkansas coal field Collier and others (this report).
Upper or western coal-bearing division, 3,000 feet.	Boggy shale, 3,000 feet.		
	Savanna sandstone, 1,200-1,500 feet.		Savanna formation.
	McAlester shale, 2,000-2,500 feet.		Paris shale, 700 feet.
			Fort Smith formation, 400 feet.
			Spadra shale, 350-500 feet.
Intermediate barren division, 500± feet.	Hartshorne sandstone, 100-200 feet	Winslow formation, 1,500 feet.	Hartshorne sandstone, 100-300 feet.
Lower or eastern coal-bearing division, 250+ feet.	Atoka shale, 2,000-7,000 feet.		Atoka formation, 1,500-5,000 feet.
		Lower Carboniferous or Mississippian rocks.	

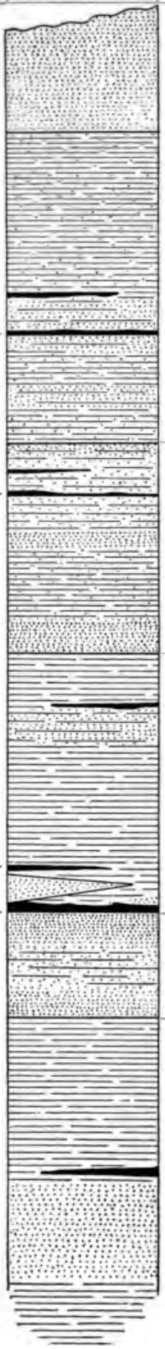
In the course of the present investigation the formations mapped in the Indian Territory coal field were traced from the Arkansas-Indian Territory boundary eastward into Arkansas with a considerable degree of success. The Hartshorne sandstone had already been located on the boundary line at three localities, Bonanza, Hackett, and the south slope of Poteau Mountain,[c] from which points its outcrop was traced without a single break in continuity eastward along the southern margin for 75 miles to the eastern end of the field. Its

---

[a] Ann. Rept. Geol. Survey Arkansas for 1888, vol. 3, pp. 10-11.

[b] Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 2, 1900, pp. 257-329.

[c] Taff, J. A., op. cit., Pl. XXXVII.

ames of coal beds.	Section	Formation and thickness in feet.	General character of formations.
		Savanna. 100-1,000.	In Indian Territory this formation comprises three sandstone members with interbedded shales; only the lower part is present in Arkansas.
aris		Paris. 600-700.	Sandy shale with thin beds of shaly sandstone. Paris coal bed about 400 feet from top.
iarleston		Fort Smith. 375-425.	Sandstone interbedded with shale. Formation yields building stones, flagstones, and brick shale. Coal beds are usually too thin for mining.
pper Hartshorne artshorne		Spadra. 400-500.	Shale with lenses of sandstone. Hartshorne coal at base is most important bed in Arkansas.
		Hartshorne. 100-300.	Typically massive sandstone, but varying to sandy shale in some places.
		Atoka. 1,500-5,000+.	Mainly shale, but sandstone lenses comprise from one-tenth to one-third of the section. Coal beds in the eastern part of the field may be thick enough in some places for mining.

GENERALIZED COLUMNAR SECTION OF THE COAL-BEARING ROCKS OF ARKANSAS.

continuity along the north side of the field is broken at a number of places and its recognition here depended on stratigraphic evidences other than continuous exposures. Nevertheless, the formation has been identified with a considerable degree of certainty in several disconnected areas within the field, along its northern border, and its character over the whole field is fairly well known.

The McAlester shale formation extends from Indian Territory into Arkansas, where it comprises the whole of the coal-bearing series. Some of the lower beds of the Savanna formation are probably also present in Arkansas, though it has not been possible to identify them with certainty at any point.

The McAlester formation as represented in Arkansas contains a group of sandstone beds near its middle portion. These were traced over a large part of the field and their stratigraphic position determined. On the geologic map herewith presented this group of sandstones is differentiated from the more shaly parts of the McAlester formation, subdividing it into three members called Spadra shale, Fort Smith formation, and Paris shale, which can be recognized throughout the field. The economic value of such a subdivision will not fail to be appreciated, since the boundaries of the formations mapped will serve as contour lines indicating approximately the depth of the Hartshorne coal horizon.

The rocks that underlie the Hartshorne formation in Arkansas have received little attention. They comprise a succession of shale and sandstone known to exceed 5,000 feet in thickness near the southern edge, but they are probably not more than 2,000 feet thick near the northern boundary of the field. In the southern part this group consists mainly of shale, but along the northern boundary the sandstone beds are much more important, making up possibly one-third of the section.

The subdivisions of the coal-bearing rocks of Arkansas, as differentiated and described in this report, are briefly tabulated as follows:

Coal-bearing rocks of Arkansas.

	Feet.
Savanna formation	200+
McAlester group:	
Paris shale	600
Fort Smith formation	400–500
Spadra shale	400–500
Hartshorne sandstone	50–400
Atoka formation	1,500–5,000

The general relations and lithologic features of these subdivisions are set forth in Pl. I.

ATOKA FORMATION.

The rocks belonging to this formation outcrop in the surrounding regions both north and south of the coal field and also occur in a number of limited areas included in it, the best known of which is that in the Backbone Ridge between Hackett and Bonanza. They have also been penetrated at a number of places by deep drill holes through the overlying rocks. South of the coal field the rocks of the Atoka formation are tilted at high angles, and extensive sections of them can be measured, but on the north their attitude is more commonly horizontal and only the upper members are exposed. In the latter region these rocks correspond in stratigraphic position with the Winslow formation as mapped by Purdue in the Winslow quadrangle.

In general the Atoka formation consists of shales with occasional sandstone beds, which in the northern part make up possibly as much as one-third of the section, while farther south the proportion of sandstone is very much less. The thickness of these rocks north of the coal field has been estimated to be approximately 1,500 feet, but near Mansfield, in the southern part, over 3,000 feet are exposed and 2,000 more have been pierced by deep drilling. The shales vary from fine-grained, black or blue clay stones to gray argillaceous sandstones. Generally the more sandy beds are harder, and where they outcrop form ridges and other prominent topographic features. Although the rocks of this formation have not been investigated in close detail, the observations made and the records of deep wells drilled through them show that the sandstone members are lenticular bodies, having no general distribution over the field. In many places where they have been examined the sandstones are very irregularly bedded, and in some places finger out into shale beds. A *characteristic* exposure of one of these beds is shown in Pl. IV, *A*.

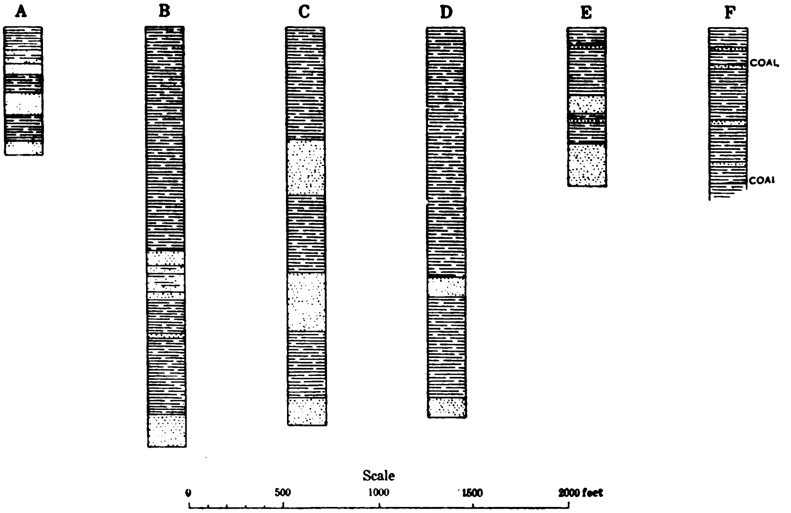


FIG. 3.—Graphic sections of the upper part of the Atoka formation. A, north of Van Buren; B, Massard Prairie; C, Jenny Lind; D, south of Huntington; E, Denning; F, Dardanelle.

The variation in the succession of sandstones and shales making up the Atoka formation is graphically shown in the sections presented in fig. 3. Lentils of coal, most of which are too thin to be of value, occur at rather infrequent intervals. Such coals seem to be more common in the eastern part of the field than in the western, a condition which may be partly due to the better exposures in the eastern portion. Some of these beds have been mined locally, and attempts to exploit them at various places are still in progress, though nearly all the old openings are deserted.

Though fossil plants have been found associated with the coal beds at several points, no satisfactory collections of them have been made. Several collections of marine invertebrates, which are described under the heading "Paleontology" (pp. 31–35), were obtained from some of the upper beds near Van Buren.

These rocks have been prospected successfully at a number of places in the search for oil and gas. The natural gas used at Fort Smith is obtained from sandstone lenses 1,000 to 2,000 feet below the top of the formation, while that at Mansfield and Huntington comes from sands 4,000 feet stratigraphically below the top of the formation.

HARTSHORNE SANDSTONE.

The Hartshorne sandstone is economically the most important formation, outside of the coal beds themselves, to be described in the district, since its outcrop indicates the position of the most important coal horizon. It had been identified at Bonanza and Hackett, on the Arkansas-Indian Territory boundary, previous to the beginning of this investigation. From these points its outcrop has been traced eastward around the end of the Backbone Ridge anticline, and its identity with the sandstone of Devils Backbone Ridge, which underlies the coal bed at Montreal and Burma, is established by drill holes at short intervals across the Greenwood syncline. From the latter localities it has been traced by continuous exposure eastward through the whole length of the coal field. The outcrop of this sandstone marks the northern boundary of the coal field through most of its length, and the rock also occurs in a number of isolated areas within the coal district, as is shown on the accompanying geologic map.

This formation is essentially sandstone, but does not differ materially from many of the heavier sandstone beds contained in the underlying rocks, except for its more general distribution over the field. Usually it can be identified by the presence of one or more coal beds in the rocks immediately above it. In its typical exposures it consists of massive, irregularly bedded rock, at most places more than 100 feet thick, and where the dips are moderately high it almost invariably makes a prominent ridge. Locally, however, the sandstone becomes shaly and in places it may consist of two comparatively thin sandstone members with sandy shale between, or it may thin out to a single sandstone less than 20 feet thick. For example, at Burma the Hartshorne is a heavy sandstone over 50 feet thick, above which there is a coal bed overlain by another sandstone of nearly equal thickness, the two beds together forming the Devils Backbone Ridge. On the north side of the Huntington basin, a few miles east of Burma, the Hartshorne formation contains only 15 feet of hard rock, and the sandstone which overlies it at Burma is absent. Though the rocks stand at a comparatively high angle, the northern rim of the basin is not marked by any noticeable ridge. A similar variation in the Hartshorne sandstone occurs near Russellville, on the north side of Shinn basin, where it consists only of sandy shales, which do not appear in the topography, although they dip at a rather high angle. South of Shinn basin, only half a mile away, the Hartshorne formation is represented by a 75-foot bed of hard sandstone, which makes a prominent ridge. Where exposed on Massard Prairie, near Fort Smith, the Hartshorne sandstone is only 10 to 12 feet thick, while farther northeast it is still thinner, and near Arkansas River it consists only of disconnected lenses of hard sandstone in a black shale. These variations in the sandstone and some detail as to its composition are shown in fig. 4. The peculiarities of bedding are illustrated in Pl. II, *B*, and Pl. III, *A* and *B*.

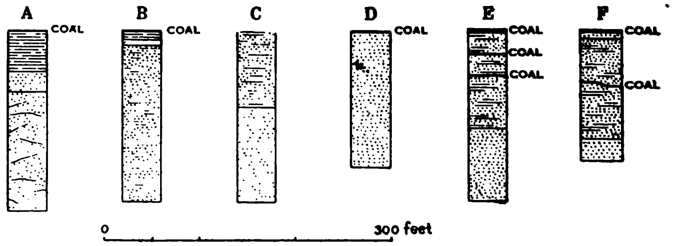
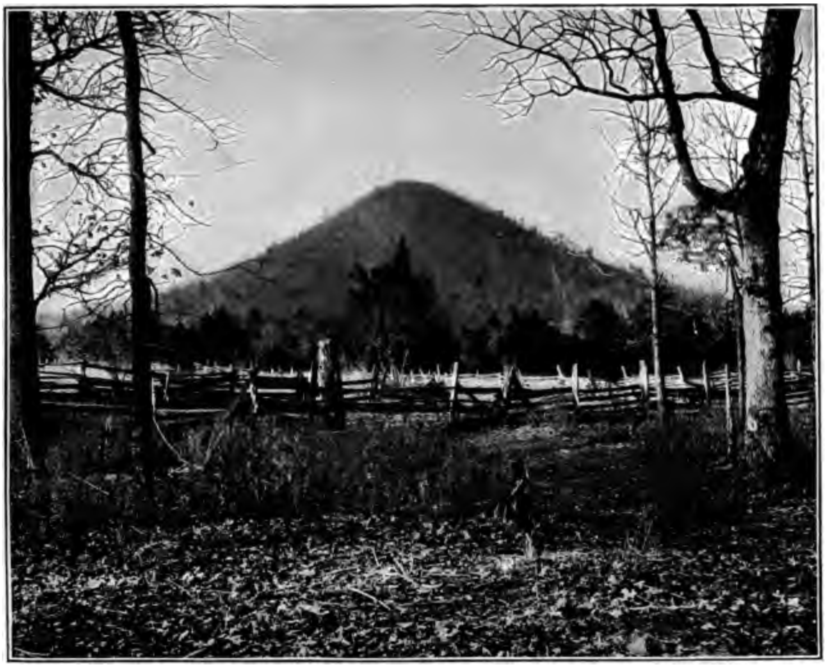


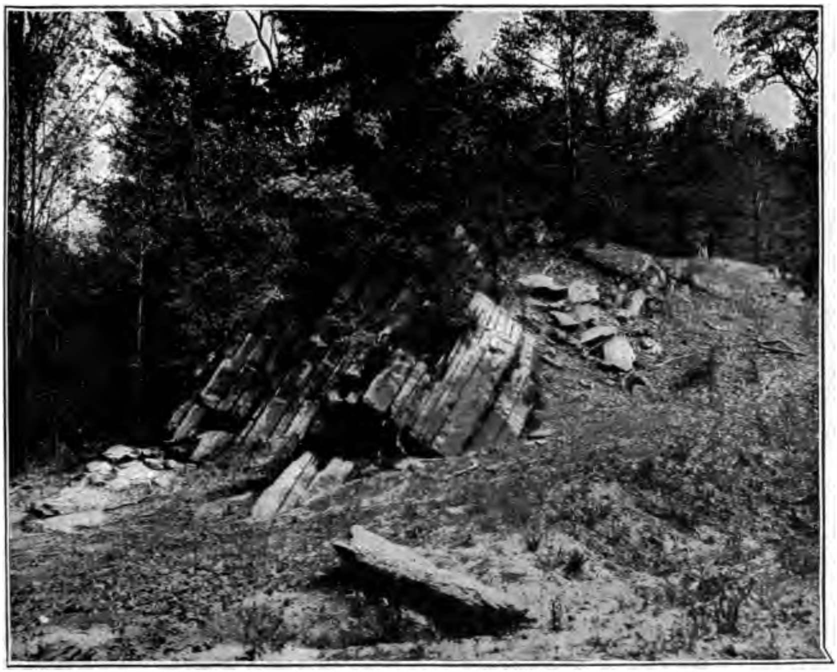
FIG. 4.—Graphic sections of the Hartshorne formation. A, Jenny Lind; B, Hackett; C, Chismville; D, Denning; E, Shinn basin; F, Ouita basin.

The coal bed which occurs in the rocks immediately above the sandstone and is called the Hartshorne coal has been traced westward into Indian Territory for 150 miles and to the eastern limits of the field in Arkansas. It is not probable that any one coal bed is continuous through this whole distance, but that there are several beds within a few feet of one another vertically, some one of which is nearly always present. In a large part of the Indian Territory field there are two coal beds, called the lower and upper Hartshorne coals, with an interval of 50 to 100 feet between them. The same two coal beds



A. VIEW OF POTATO HILL.

A cone-shaped butte formed by the erosion of horizontally bedded shales in a synclinal basin.



B. *EXPOSURE OF* HARTSHORNE SANDSTONE SOUTH OF SHINN BASIN.

Showing one of many phases of the Hartshorne sandstone.

are present in the southwestern part of the Arkansas field, near Montreal and Burma, but in other parts of the field only one of them, probably the lower, has been found.

This formation is barren of fossil remains, neither plants nor invertebrates having been found in it, with the exception, possibly, of a few fragments of *Stigmaria*. At many places, however, lumps of mud are included in the sand, which on weathering out leave cavities resembling those left by fossil invertebrates. This sandstone is not known to have yielded natural gas or oil, though it has yielded good flows of artesian water at several places, where drill holes have penetrated it.

SPADRA[a] SHALE.

The Spadra shale, named from the town of Spadra, in Johnson County, stands next in economic importance to the Hartshorne sandstone, which it overlies, since at its base it contains the most important coal beds. It is well known to coal operators and miners in Arkansas, being represented at nearly all of the mining towns. This formation is distributed over the whole of the workable coal field and its outcrop is eroded in many places to form broad valleys, many of which were indicated on the older maps of the region, where they are described as prairies. The residual soil it produces seems to be comparatively poor and the vegetation on it is relatively scant. In general this formation consists of fine-grained blue, black, or gray clay shales, but locally it contains sandy beds and in some places thin sandstone lenses, none of which extend for very great distances. The most prominent sandstone lens observed is one near Burma, in Sebastian County, which forms the parting between the upper and lower Hartshorne coals. This sandstone which has a maximum thickness of 60 feet, is irregularly cross-bedded, contains mud lumps, and resembles the Hartshorne sandstone in hardness, but it thins out and disappears within a few miles in each direction from its thickest part. At many other places sandstones having a thickness as great as 20 feet occur, but these are of irregular distribution and of no great extent. The thickness of the formation, which is well known not only from surface observations but from many drill holes that have penetrated it, varies from 350 to 500 feet. These differences may be due to either one of two causes—either the shale beds themselves vary in thickness in different parts of the field, or, as seems more likely, some of the sandy members at the base of the overlying formation thin out locally and disappear. The formation appears to be abnormally thin where it outcrops along the southern edge of the central part of the field, in some sections not exceeding 200 feet in thickness.

---

[a] The name Spadra stage, applied to the time this formation was deposited, was published by John J. Stevenson in 1895. Trans. New York Acad. Sci., vol. 15, 1896, p. 51.

This condition is attributed tentatively to the rather intense local folding of the beds, it being inferred that the softer shale has been either squeezed or sheared. A number of characteristic sections of the Spadra shale taken from various parts of the field are shown in fig. 5.

Fossil plants and occasionally invertebrate animal remains occur in the shale overlying the Hartshorne coal bed and representative collections were made from it at several localities. These collections have been examined by David White and G. H. Girty, whose reports on them are given in full on pages 24–35 of this paper. Although the Spadra shale has a flora that is to a certain extent characteristic of it, many of the species represented have also been collected from beds much higher in the stratigraphic column and therefore such collections of fossils are of little value in correlating formations in different parts of the field. The various fossils collected from these coal measures indicate that they were deposited very rapidly as compared with those of eastern coal fields.

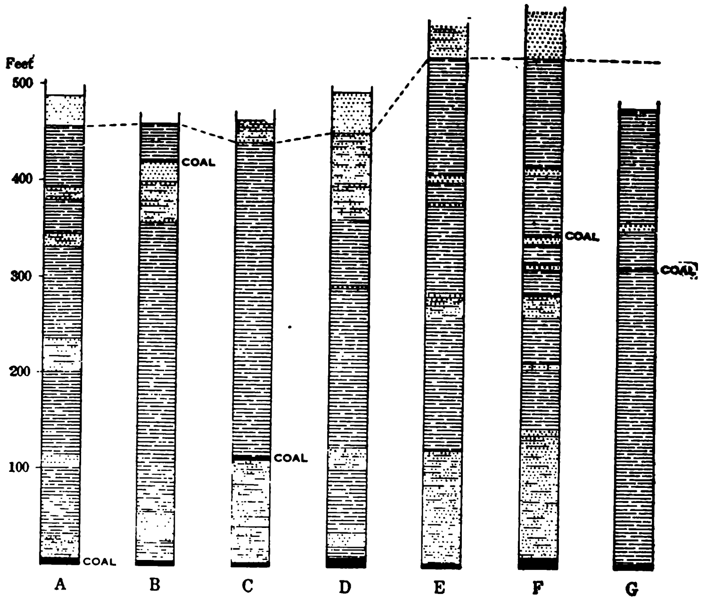
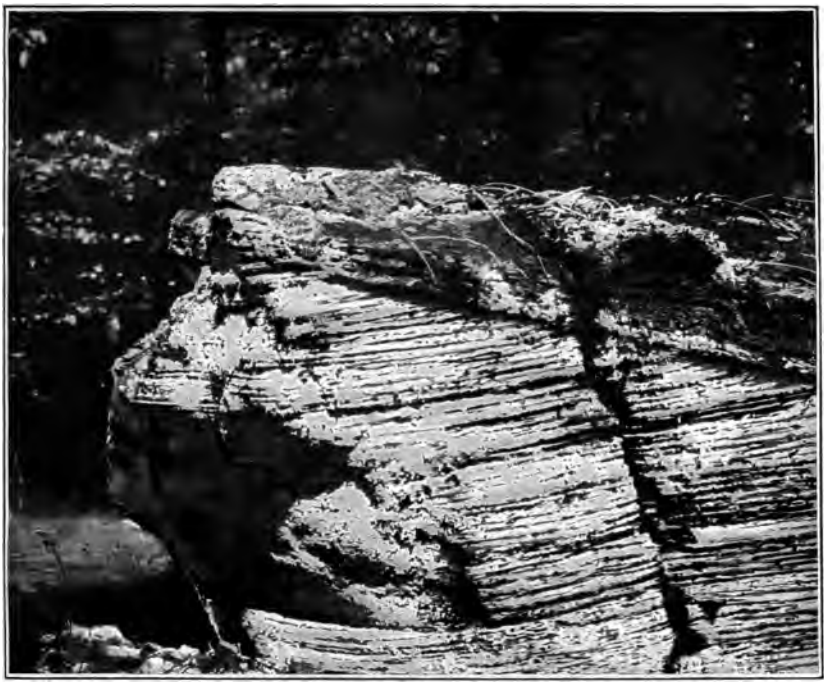


FIG. 5.—Graphic sections of Spadra shale. A, north of Jenny Lind; B, northwest of Midland; C, southwest of Hartford; D, east of Greenwood; E, north of Prairie View; F, east of Spadra; G, Shinn basin.

These shales have been used to a limited extent near Fort Smith for brickmaking, but otherwise they have no economic value except for the coal beds.

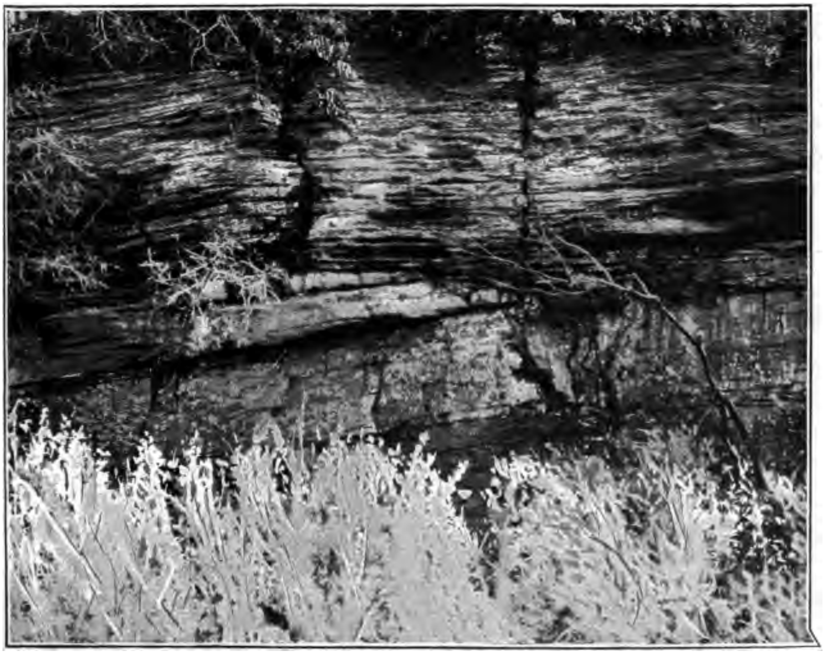
FORT SMITH FORMATION.

The outcrops of the Fort Smith formation are more widely distributed than those of any other formation within the coal field, as



A. EXPOSURE OF THE HARTSHORNE SANDSTONE NEAR PINEY CREEK EAST OF KNOXVILLE.

Showing the false bedding characteristic of this formation in some places.



B. APPARENT *UNCONFORMITY* IN HARTSHORNE SANDSTONE, DUE TO FALSE BEDDING.

Illustrating another phase of irregularity in the bedding.

is shown by the geologic map. The formation consists of a group of thin and to some extent variable sandstone beds, with interbedded shale members, and is named from the city of Fort Smith, in Sebastian County. In general the sandstones are ripple-marked, the markings presenting considerable variety in both size and form, and many of the individual beds are characterized by a wavy cleavage approximately parallel to the minor undulations of the bedding planes. False bedding or cross-bedding, which is a common feature of the Hartshorne sandstone, is unusual in the Fort Smith formation, though it is not entirely absent. The shales are nearly everywhere more or less arenaceous and the resulting soils are reddish or yellowish and sandy. At Fort Smith the lower sandstone member is extensively quarried and has yielded most of the flagstones with which the city is paved. The formation here consists of a lower member,. 20 to 50 feet thick, of hard, flaggy, ripple-marked sandstone, above which there are 40 to 60 feet of shale overlain by hard sandstone and shaly sandstone nearly 100 feet thick. Near the upper part of the formation there is a coal bed which was formerly mined and which appears on the map prepared by the Geological Survey of Arkansas as the Hermann and Wilson pits.

One of the best exposures of the formation is found in the region east of Greenwood. Here the lower sandstone member, which is probably identical with that at Fort Smith, forms a prominent ridge constituting the rim of a synclinal basin in which the town of Bloomer is situated. Above this sandstone is nearly 200 feet of shale, which is overlain by a series of hard, shaly sandstones forming Grand and Coal ridges, aggregating about 200 feet in thickness. There are two coal beds in the upper part of the formation here, the lower one of which has been opened in a number of pits and varies in thickness from 18 inches to 3 feet. The lower sandstone member of the formation is also typically exposed in Tennessee Ridge, which forms the northern wall of Long Prairie at Jenny Lind, and from this occurrence it has been locally called the "Tennessee sandstone."

The individual beds comprising this formation in the eastern end of the field have not been definitely correlated with those in the western part. In the vicinity of Spadra it is probable that the lower sandstone member corresponding to the sandstone of Tennessee Ridge is either absent or so shaly that it can not be identified, while a bed a little higher stratigraphically has taken its place as the first distinct sandstone above the Spadra shale. This sandstone forms the escarpment at the front of Big Danger Hill south of Clarksville and is about 60 feet thick.

The upper part of the Fort Smith formation is probably not represented in this part of the field. In general the formation here is much more sandy than the Spadra shale. It contains several small, unimportant coal beds, which have not been examined in detail nor correlated with those in the western part of the field.

The average thickness of the Fort Smith formation is estimated at 400 feet. Detailed sections exposed at various localities are shown in fig. 6.

Fossil plants occur in association with some of the coal beds, and several collections made from them have been examined by David White, who refers to them as the Coal Ridge flora. This flora seems to differ only slightly from that of the Hartshorne horizon, though it can be distinguished.

The sandstones of this formation have been quarried for paving and building stones at several places. At Fort Smith the lower sandstone member has been extensively worked, yielding flagstones from which most of the city's sidewalks are made. These flags are from 3 to 6 inches thick and, though hard and durable, their surfaces are invariably ripple-marked and rough.

At Cabin Creek station (Lamar post-office), in the eastern part of the field, a more massive bed, somewhat higher in the formation, is quarried, yielding a good stone, which is shipped to more distant markets, some of it going as far as New Orleans. A view of this quarry showing the characteristic bedding and joint planes of the rock is shown in Pl. IV, *A*.

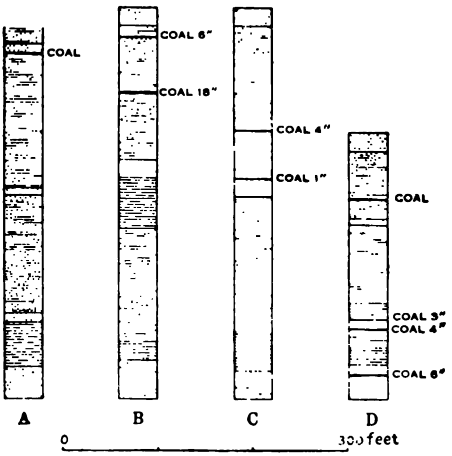
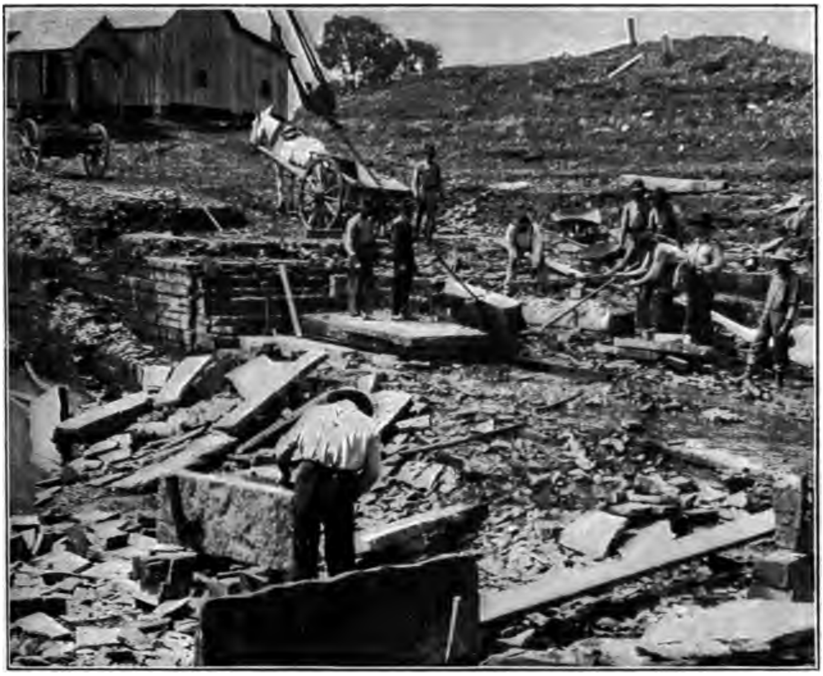


FIG. 6.—Graphic sections of the Fort Smith formation. A, section at Fort Smith; B, section north of Auburn; C, section north of Prairie View; D, section northeast of Lamar.

The rock quarried at Spielerville and used in the construction of the Subiaco College buildings is probably taken from a sandstone bed in this formation, and most of the brick factories near Fort Smith have obtained their material from shale beds that are included in it.

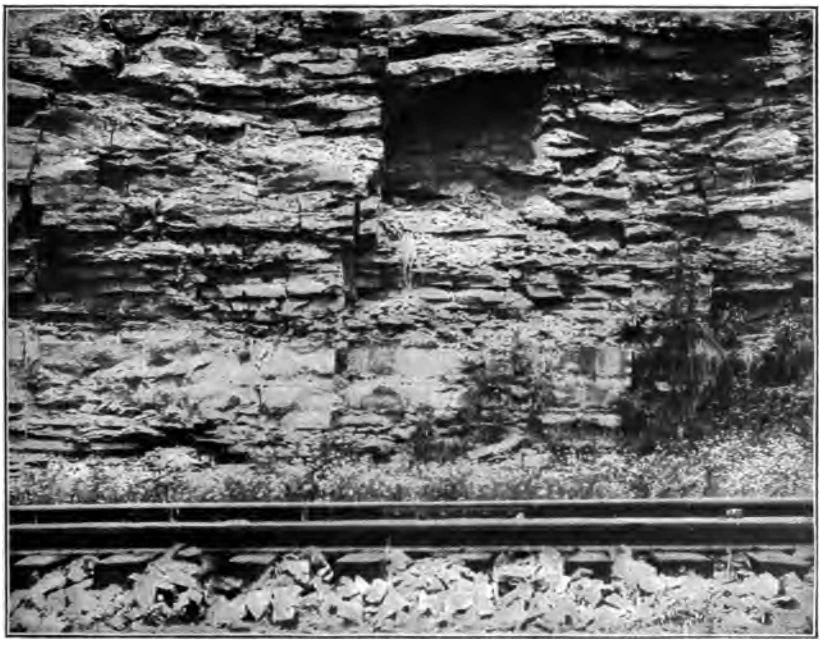
PARIS SHALE.

The Paris shale, which takes its name from the town of Paris in Logan County, covers two large areas, essentially broad synclinal basins, in the central part of the field. One syncline near Paris is surmounted by Short and Little Short mountains. The other, south of Charleston, surrounds the base of Potato Hill. It also occurs in smaller areas in Sugarloaf, Poteau, and Magazine mountains. The *base of the formation* is believed to be nowhere less than 800 feet *above the horizon* of the Hartshorne coal. This formation resembles



A. QUARRY AT CABIN CREEK.

Illustrating the system of jointing which prevails over the Arkansas coal field.



B. SANDSTONE OF ATOKA OR WINSLOW FORMATION, ONE-HALF MILE WEST OF OZARK.

Illustrating a type of *irregular bedding* characteristic of certain sandstones below the coal-bearing rocks.

padra shale, but is almost invariably more sandy and contains a er number of sandstone lenses, whose distribution has not been mined in close detail. The sandstone lenses, however, are generofter than those included in the Spadra formation and do not conso strongly in topographic expression with the including shales. e total thickness is estimated from the dips of the outcrops to tween 600 and 700 feet. Its upper limit is marked in the Paris by the base of the heavy sandstone which caps Short and Little t mountains. Detailed sections of the formation as exposed at t Mountain and Potato Hill are given in fig. 7.

e Paris coal bed occurs from 200 to eet above the base of the Paris formaand about 400 feet below its upper . A large collection of fossil plants nvertebrate animal remains from the y shale in the roof of this bed was itted to David White and G. H. Girty, e reports are given on pages 24–35. e flora resembles that from the Coal e horizon but is provisionally correwith that from above the McAlester bed of Indian Territory, which occua similar relation to the Hartshorne horizon. Except for its coal this ation yields no minerals of economic . Its sandstones are usually too for building purposes and its shales not been utilized in brick-making.

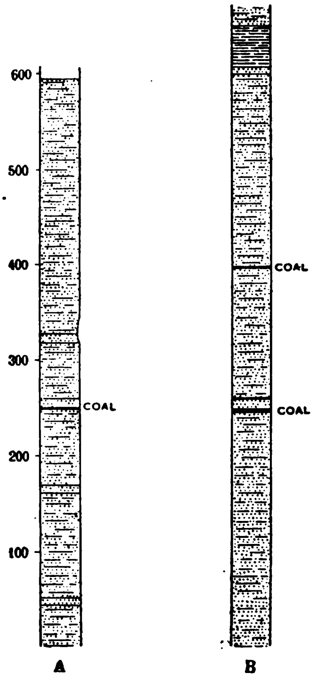


FIG. 7.—Graphic sections of Paris shale. A, Potato Hill; B, Short Mountain.

SAVANNA FORMATION.

e Savanna sandstone occurs in only v small areas in Arkansas, where it several isolated mountains and buttes. formation as represented in Indian tory is described as a group of three more or less massive and sandstone beds with intervening shaly members, the total ness being approximately 1,000 feet. In Arkansas only the r part of this formation is present. Short and Little Short ntains near Paris are regarded as type localities. At Short ntain the Savanna is represented by a massive sandstone y 100 feet thick, which lies as a flat cap forming a mesa on the nit. The conditions are similar at Little Short Mountain, which pped by the same bed. The sandstone beds at the top of Maga-Mountain, which are provisionally correlated with the Savanna, a total thickness of several hundred feet and contain some coneratic beds with quartz and chert pebbles as large as one-eighth of an inch in diameter. This formation is also represented in Sugarloaf and Poteau mountains, where the detail of its beds is so obscured by talus that it has not been mapped closely.

In general the Savanna formation has little economic value in Arkansas. No coal beds have yet been discovered in it, though such beds may be present in Poteau and Sugarloaf mountains. The sandstone beds in Short Mountain are massive and could probably be used for building stones where large blocks are required.

SURFICIAL DEPOSITS.

Many of the lowland areas within the coal field are mantled over with deposits of silt, sand, or gravel that were laid down on surfaces formed by the erosion of the coal-bearing rocks. As noted above, there are remnants of several old plain surfaces representing different stages of erosional development in Arkansas Valley. The most recent stage is represented by the flood plains of Arkansas River and its tributary streams. A somewhat earlier stage is indicated by the general lowland area above the flood-plain level, while a much earlier stage is represented by the level-topped ridges and hills surmounting this lowland. The difference in elevation between the highest and lowest plain is about 400 feet. Deposits of gravel and sand are of wide distribution on the surfaces representing the two later stages, where they have received casual attention. These deposits are evidently distinct in age, though it is often hard to differentiate them in the field. On the accompanying geologic map, Pl. VI, they are indicated only in those areas where they are so thick as to conceal effectually the underlying strata and render it impossible to discover the geologic relations of the coal-bearing rocks. The recent deposits are not differentiated from the earlier ones.

The recent deposits, which are most extensively represented in the flood plains of Arkansas River, are composed generally of rather fine silt and sand, gravels and coarse pebbles being of rare occurrence. Their surfaces are marked by oxbow lakes and other ordinary flood-plain features. They comprise much of the richest agricultural land in this district, though they are subject to overflow at long intervals.

The earlier of these deposits, where identified, usually consist of sand and moderately fine gravel containing many pebbles of chert. Generally they are indicated by waterworn pebbles strewn over the surface, but in good exposures, such as banks of streams and road cuts, they are stratified and are often 20 feet or more in thickness. Such deposits are invariably more or less eroded and show none of the original surface features of flood-plain deposits.

Flat surfaces of this lowland plain of the earlier period are in many places marked by scattered low mounds[a] averaging 2½ feet in height by 50 feet in diameter, whose origin has been the subject of much speculation.

---

[a] Campbell, M. R., Natural mounds: Jour. Geol., vol. 14, No. 8, November-December, 1906. This paper is one of the latest and most comprehensive discussions of this subject and contains a bibliography of the literature relating to it.

The mounds generally occur in localities of poor drainage, and in Arkansas are especially common over clay soils formed by the disintegration of the shale beds, though not confined to them exclusively. The general distribution of the mounds, not only here but in other States, disproves the theory very common in Arkansas that they are formed by escaping gases and are therefore good indications of gas, oil, or coal. Of the other hypotheses regarding them the one that they were built by burrowing animals of some kind now extinct seems to the writer most probable. At any rate they were produced under conditions not now existing in Arkansas Valley, and they can safely be taken as an infallible diagnostic feature of the older erosion levels and surficial deposits.

PALEONTOLOGY.

CONCLUSIONS DRAWN FROM STUDIES OF THE FOSSILS.

Fossils representing the plant and animal life of the coal period are not generally distributed through the Arkansas coal measures, though they are abundant in certain beds at a few horizons where a number of fairly representative collections have been made. The fossil plants collected for the Arkansas Geological Survey were examined and reported on in a paper by H. L. Fairchild and David White which, like several other reports of that organization, has unfortunately never been published. Several collections of invertebrate fossils from the coal field were identified, described, and illustrated by Prof. J. P. Smith,[a] formerly of the Arkansas Survey, and the correlation of the coal measures with Carboniferous rocks of other regions was adequately discussed by him in several papers published by private organizations, which are available for reference in any good geological library.

Since the discontinuance of the Arkansas Geological Survey, many collections, of both plants and marine invertebrates, from corresponding rocks in Indian Territory, have been examined by David White[b] and G. H. Girty,[c] and are described in the publications of the United States Geological Survey.

The collections made in the course of the present investigations in Arkansas have been examined by Messrs. White and Girty, whose reports on them are presented on pages 24–35. In general these fossils afford little ground for the stratigraphic correlation of individual beds and horizons, though they determine in a general way the age or time relations of the coals of Arkansas as compared with those of other States. Two conclusions of general interest may be drawn from a study of the fossils:

---

[a] Smith, James Perrin, The Arkansas coal measures in their relation to the Pacific Carboniferous province: Jour. Geol., vol. 2, 1894, pp. 187-203; Marine fossils from the coal measures of Arkansas: Proc. Am. Philos. Soc., vol. 35, 1896, pp. 214-285, Pls. XVI-XXIV.

[b] White, David, Report on fossil plants from the McAlester coal field, Indian Territory, collected by Messrs. Taff and Richardson in 1897: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 3, 1899, pp. 457-534, Pls. LXVII-LXXVIII.

[c] Girty, G. H., Preliminary report on Paleozoic invertebrate fossils from the region of the McAlester coal field, Indian Territory: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 3, 1899, pp. 539-593, Pls. LXIX-LXXII.

1. The Arkansas coal measures correspond to a lower part of the Pennsylvanian series of the Carboniferous.. They are somewhat older than the coals of Kansas and younger than those of Alabama.
2. The great thickness of coal-bearing sediments of Arkansas was deposited in a relatively short time as compared with that required for the deposition of the corresponding rocks in Pennsylvania and West Virginia. The rapid sedimentation may account for the great stratigraphic intervals between the several coal beds and for much of the irregularity in the bedding.

REPORT ON FOSSIL PLANTS FROM THE COAL MEASURES OF ARKANSAS.

By David White.

EXTENT AND CHARACTER OF THE COLLECTIONS.

The fossil plants collected by Mr. Arthur J. Collier and assistants from the Arkansas coal fields have been examined very closely, and the identifications listed below are, for the most part, final, though a portion are subject to revision and must be regarded as preliminary.

A fact that becomes at once apparent on inspecting the plants collected by Mr. Collier is the remarkable lack of strong or characteristic differences between the ferns of the upper and lower horizons represented in the collections. The entire period covered by the approximately 1,200 feet represented therein is not greater than that embraced in less than 200 feet of a corresponding portion of the Allegheny formation in the Appalachian trough. The Coal Hill coal appears paleobotanically at the level of the Brookville coal in the Allegheny formation. The Coal Ridge flora, on the other hand, is perhaps not younger than the lower Kittanning coal of the Allegheny formation, while the Paris coal furnishes no evidence of a date later than upper Kittanning. The entire interval falls within the limits of the Cherokee formation in Kansas, and of the basal coal measures in Henry County, Mo., including beds probably not over 150 feet above the Mississippian surface.

In view of this great dilation of the basal Allegheny and consequent extraordinarily rapid sedimentation it is not surprising that very little distinct change is to be observed from one point to another, or that the horizons can with difficulty be detected paleobotanically without elaborate collections. Some of the lots contain but few species, many of which have considerable vertical range. It is impossible, therefore, to foresee what similarities between certain lots would appear if the collections were more complete. On the contrary, where the collections are from very different horizons it is safe to infer that larger collections would show greater paleontological differences.

In listing and discussing the collections I shall treat them in several natural groups, which are assumed to represent as many horizons or phases of the floras. A small number of lots will be omitted on account of the absolute insufficiency of the material.

FLORA OF THE COAL HILL COAL.

The collections which I regard as probably belonging to this horizon represent a basal Alleghenian flora in which a few traces of Pottsville development are still to be seen, as illustrated particularly in *Mariopteris* and *Neuropteris*.

Fossil plants (lot D) from NE. ¼ SE. ¼ sec. 29, T. 9 N., R. 25 W., below Coal Hill coal.

Annularia sphenophylloides.
Sphenophyllum emarginatum.
Sphenophyllum suspectum.
Pseudopecopteris macilenta.
Cheilanthites trifoliolatus.
Cheilanthites squamosus.
Mariopteris occidentalis.
Mariopteris nervosa.
Pecopteris vestita.
Pecopteris (Scolecopteris) cf. miltoni.
Alethopteris serlii (lax).
Neuropteris capitata.
Neuropteris missouriensis.
Neuropteris scheuchzeri.
Neuropteris rogersii.
Linopteris squarrosa?.
Dolerophyllum angularis.
Cardiocarpon bicuspidatum?.
Rhabdocarpos sulcatus.

Fossil plants (lot E) from NE. ¼ sec. 24, T. 9 N., R. 26 W., west of Coal Hill.

Annularia sphenophylloides.
Sphenophyllum emarginatum var. minor.
Sphenophyllum suspectum.
Cheilanthites squamosus.
Mariopteris occidentalis.
Mariopteris nervosa.
Pecopteris plumosa.
Pecopteris vestita?.
Pecopteris sp., indet. fragment.
Alethopteris serlii.
Neuropteris scheuchzeri.
Wing of cockroach.

Fossil plants (lot B) from Southern Anthracite Coal Company's shaft No. 1, at Russellville, Ark., in sec. 16, T. 7 N., R. 21 W.

Annularia sphenophylloides.
Calamostachys sp.
Sphenophyllum fasciculatum.
Cheilanthites squamosus.
Mariopteris occidentalis.
Pecopteris vestita?.
Alethopteris serlii.
Aphlebia cf. hirsuta.
Neuropteris missouriensis.
Neuropteris capitata.
Neuropteris scheuchzeri.
Sigillariostrobus quadrangularis.
Wing of cockroach.

Fossil plants (lot C) from Humphrey's shaft, north of Russellville, Ark., in sec. 28, T. 8 N., R. 21 W.

Annularia radiata.
Annularia sphenophylloides.
Sphenophyllum emarginatum var. minor.
Mariopteris latifolia?.
Neuropteris *cf. tenuifolia.*
Neuropteris harrisii?.
Neuropteris missouriensis.
Neuropteris scheuchzeri.
Wing of cockroach.

Fossil plants (lot M) from Woodson's strip pit, one-fourth mile north of Burma station on the Frisco Railway, in sec. 19, T. 5 N., R. 31 W.

Annularia sphenophylloides.
Sphenophyllum emarginatum.
Alethopteris serlii.
Neuropteris harrisii.
Neuropteris missouriensis.
Neuropteris ovata.
Neuropteris cf. tenuifolia.

Fossil plants (lot C) from old No. 1 mine at Denning, Ark., in SE. ¼ sec. 22, T. 9 N., R. 26 W.

Annularia stellata.
Annularia sphenophylloides.
Phyllotheca ? sp.
Sphenophyllum emarginatum.
Sphenophyllum majus.
Sphenophyllum suspectum.
Cheilanthites squamosus.
Mariopteris incompleta.
Mariopteris muricata.
Mariopteris occidentalis.
Mariopteris nervosa.
Sphenopteris sp.
Pecopteris emarginata.
Pecopteris cf. robusta.
Pecopteris vestita.
Pecopteris clintoni?.
Alethopteris serlii (lax).
Neuropteris capitata.
Neuropteris missouriensis.
Neuropteris scheuchzeri.
Lepidophloios scoticus?.
Sigillariostrobus quadrangularis.

The four lots first listed above appear to represent an identical flora. The plants in lot C show so close a relation to the flora of the Hartshorne coal of Indian Territory as in my judgment to justify the belief that it belongs to the same horizon—a conclusion sustained also by lot M.

Fossil plants (lot I) from NE. ¼ SW. ¼ sec. 29, T. 9 N., R. 25 W., southwest of Coal Hill.

Sphenophyllum emarginatum.
Mariopteris occidentalis.
Mariopteris nervosa.
Alethopteris serlii.
Neuropteris missouriensis?.
Rhabdocarpos sulcatus.
Rhabdocarpos ? sp.

The very small collection listed above is placed here on account only of its lack of difference from the preceding. In itself it is insufficient for paleontological correlation.

Fossil plants (lot K) from mine No. 4 Western Coal Company, in NW. ¼ SE. ¼, sec. 19, T. 9 N., R. 25 W., west of Coal Hill.

Neuropteris missouriensis.
Neuropteris scheuchzeri.
Lepidophyllum missouriense.
Asolanus camptotænia.
Cardiocarpon cf. circulare

This very meager collection differs from the other floras by the addition of two lepidophytes and by the relatively small number of ferns. Its inclusion with the Coal Hill flora is based purely on the stratigraphic data furnished by Mr. Collier.

FLORA OF THE SPADRA COAL.

The two collections next listed come from below the Spadra coal.

Fossil plants (lot H) from shale 4 feet below Spadra coal in old Allen slope, in NE. ¼ sec 13, T. 9 N., R. 25 W., northwest of Hartman, Ark.

Annularia sphenophylloides.
Eremopteris cf. lincolniana.
Pseudopecopteris macilenta.
Mariopteris sp. cf. sphenopteroides? indet. fragment.
Sphenopteris cf. cristata.
Pecopteris vestita.
Alethopteris serlii.
Neuropteris ovata.
Neuropteris capitata?.
Neuropteris jenneyi.
Linopteris cf. squarrosa; small fragment.

Fossil plants (lot G) from SE. ¼ sec. 24, T. 10 N., R. 25 W., 4 miles north of Hartman, Ark.

Annularia sphenophylloides.
Eremopteris cf. lincolniana.
Pseudopecopteris macilenta.
Sphenopteris (Hawlea) cf. cristata?. Small fragment.
Pecopteris vestita?.
Aphlebia hirsuta.
Alethopteris serlii.
Neuropteris scheuchzeri.
Neuropteris jenneyi.
Linopteris cf. squarrosa.
Sigillariostrobus quadrangularis.

While apparently as old as the Coal Hill flora these two lots are not so far identical with the latter as might be expected. The two lots are very nearly identical in composition and it is possible that their difference from the flora of the Coal Hill coal may be due only to the fact that the fossils come from below the coal rather than from the roof shale.

The interesting feature connected with the Spadra flora is the occurrence of *Pseudopecopteris macilenta*, *Neuropteris jenneyi*, and *Linopteris squarrosa*, three species originally described from the small outlying basin in the zinc region of southwestern Missouri.

FLORA OF THE COAL RIDGE OR CHARLESTON COAL.

Fossil plants (lot L) from Carter's coal mine, in sec. 17, T. 7 N., R. 28 W., southeast of Charleston, Ark.

Annularia sphenophylloides.
Sphenophyllum emarginatum var. minor.
Sphenophyllum fasciculatum.
Sphenopteris sp. indet. fragment.
Aloiopteris winslovii.
Pecopteris vestita.
Pecopteris miltoni?.
Callipteridium membranaceum.
Neuropteris missouriensis.
Neuropteris scheuchzeri.
Lepidophyllum lanceolatum.
Cordaites (communis ?).

Fossil plants (lot Q) from point 50 paces south of iron bridge, one-half mile east of Caulksville, Ark., in sec. 3, T. 7 N., R. 17 W.

Annularia sp.
Sphenophyllum emarginatum.
Sphenophyllum majus.
Eremopteris spinosa.
Neuropteris cf. rarinervis.
Neuropteris cf. missouriensis ?.
Neuropteris scheuchzeri.
Linopteris münsteri.
Lepidocystis vesicularis.

Fossil plants (lot N) from sec. 3, south center, south of bridge east of Caulksville, Ark., in sec. 3, T. 7 N., R. 27 W.

Annularia sphenophylloides.
Sphenopteris cf. illinoisensis.
Renaultia sp. indet.
Pecopteris villosa?.
Pecopteris oreopteridia.
Pecopteris candolliana.
Neuropteris missouriensis.
Linopteris münsteri.
Lepidophyllum ovatifolium?.

Fossil plants (lot P) from shale over Coal Ridge or Charleston coal in northeast corner sec. 6, T. 7 N., R. 28 W., north of Charleston, Ark.

Asterophyllites equisetiformis.
Sphenopteris ? sp. indet.
Pecopteris vestita.
Neuropteris scheuchzeri.
Linopteris münsteri.

The plants contained in lots L, Q, and N belong to a flora which, though very closely allied to that of the Coal Hill coal, appears, nevertheless, to differ from the latter by the absence of some of the earlier forms related to *Cheilanthites*, *Mariopteris*, and *Neuropteris*. The flora is fairly homogeneous, though not rich. It is characterized by the presence of a considerable number of species which were not collected from the Coal Hill coal and which point to an approximate contemporaneity with the lower coal in Henry County, Mo. It is doubtful whether the flora here represented is younger than the Lower or Middle Kittanning, though it is possible that more complete collections will prove it to be young as the Upper Kittanning. Strictly speaking, this flora is perhaps as high as any that is represented in the collections. The five species of lot P are tentatively placed in the same group with L and Q, on account of the identity of the *Linopteris münsteri*. The flora of lot P itself is too small for correlative value.

THE PARIS FLORA.

Fossil plants (lot O) from coal seams of the Paris Coal Company, in sec. 10, T. 7 N., R. 26 W., one-half mile west of Paris, Ark.

Calamites suckowii.
Cheilanthites trifoliolatus.
Linopteris münsteri (abundant).
Lepidophyllum lanceolatum.
Lepidostrobus sp. (small).
Sigillaria discophora.
Androstachys? sp. indet.

This flora, which is possibly the youngest represented in the collections, appears to be closely joined to the preceding by the very abundant *Linopteris münsteri*. The remaining species are, however, largely unrepresented in the other collections, but their general stratigraphical significance is not such as to permit of regarding the Paris coal as very much later in date than the Coal Ridge coal. I do not regard it as younger than Upper Kittanning.

LOTS OF DOUBTFUL AGE.

Hereunder I list the collections in lots V, W, U, and X, all of which are probably from the same horizon. It would seem that these lots can not be younger than the Coal Ridge flora, while, on the other hand, the number of species which they hold in common with the Coal Hill flora would at first make them seem susceptible of reference to the latter horizon. At the same time each lot contains so large a proportion of forms not represented in the collections from Coal Hill coal as to leave some doubt as to the correctness of such a reference. The general indications of some of these extraneous species would seem to preclude considering the material as later, at furthest, than Coal Ridge flora. This is particularly true of lot V, whose connection with the Coal Hill flora is less evident than appears in the case of lot U. I am, on the whole, slightly more disposed to regard them as representing the Coal Hill coal. At the same time the presence of the species whose general status would seem to point to a higher horizon must leave doubt as to whether collections U and V are not, perhaps, as young as the Coal Ridge coal. Lots X and W are listed in connection with lots U and V for the reason only that they are too limited in species to present any differences from the other lots.

Fossil plants (lot V) from NW. ¼ NE. ¼ sec. 23, T. 9 N., R. 27 W., 5 miles west of Altus, Ark.

Calamites sp. indet.
Annularia sphenophylloides.
Sphenophyllum emarginatum.
Sphenophyllum fasciculatum.
Mariopteris sphenopteroides.
Mariopteris nervosa.
Sphenopteris cf. pinnatifida.
Crossotheca ophioglossoides.
Pachypteris gracillima.
Pecopteris vestita.
Neuropteris rarinervis.
Neuropteris missouriensis.
Neuropteris clarksoni?.
Neuropteris ovata.
Neuropteris scheuchzeri.
Odontopteris bradleyi?.
Lepidodendron sp., indet. twig.
Lepidophyllum oblongifolium.

Fossil plants (lot W) from SW. ¼ sec. 17, T. 9 R. 26 W., N. 2, miles west of Altus, Ark.

Calamites ramosus.
Annularia sphenophylloides.
Mariopteris nervosa.
Pecopteris villosa?. Fragments.
Wing of cockroach.

Fossil plants (lot U) from near Central Coal and Coke Company's mine at Hartford, in sec. 15, T. 4 N., R. 32 W.

Annularia sphenophylloides.
Sphenophyllum emarginatum var. minor.
Sphenophyllum cf. majus.
Cheilanthites squamosus.
Mariopteris occidentalis.
Mariopteris incompleta.
Mariopteris sphenopteroides.
Aloiopteris winslovii.
Pecopteris vestita.
Pecopteris candolliana.
Pecopteris dentata.
Pecopteris jenneyi?.
Alethopteris serlii var missouriensis.
Neuropteris ovata.
Neuropteris scheuchzeri.

Fossil plants (lot X) from sec. 21, T. 10 N., R. 29 W., 2 miles west of Pleasant Hill, on old wire road.

Sphenopteris sp.
Alethopteris serlii.
Neuropteris ovata.
Neuropteris scheuchzeri.

THE VAN BUREN FLORA.

Fossil plants (lot T) from E. ½ SE. ¼ sec. 9, T. 9 N., R. 31 W.

Asterophyllites equisetiformis.
Annularia radiata.
Annularia sphenophylloides.
Sphenophyllum emarginatum.
Sphenophyllum fasciculatum?.
Cheilanthites pluckenetii.
Mariopteris sphenopteroides.
Mariopteris occidentalis.
Mariopteris nervosa.
Crossotheca ophioglossoides.
Sphenopteris cf. mixta.
Pecopteris vestita?.
Pecopteris villosa.
Pecopteris robusta?.
Pecopteris dentata.
Aphlebia hirsuta.
Alethopteris serlii.
Callipteridium inæquale?.
Callipteridium sullivantii.
Neuropteris ovata.
Neuropteris fimbriata.
Neuropteris missouriensis.
Neuropteris scheuchzeri.
Neuropteris clarksoni?.
Cordaites cf. principalis.
Cordaianthus sp.
Cardiocarpon fluitans.
Rhabdocarpus sp.

The review of the species listed above shows at once that the Van Buren flora is most intimately associated with that represented by lots U and V. Its species are identical with the former, but they are, by the generally recognized range of the forms, shown to be of approximately the same age. The Van Buren flora (lot T) is therefore, I believe, to be considered as not younger than the Coal Ridge flora. If it can be shown that lots V and W are as old as Coal Hill it will then be possible to refer lot T to nearly as low an horizon. In this connection it may be of interest to compare lots U and V, as well as T, with two collections made by Mr. Taff from the Poteau and Sallisaw quadrangles of Indian Territory. I am not informed as to the stratigraphical position of the Indian Territory floras, though it is probable that Mr. Taff can readily supply the data; but it is desirable to call attention to the strong evidence of approximate contemporaneity which would appear to exist between these localities and those of the lots last discussed.

Fossil plants (lot 2180) from lower coal at Witteville, Ind. T. (Poteau quadrangle), in NE. ¼ sec. 15, T. 7 N., R. 25 E.

Sphenophyllum emarginatum.
Cheilanthites squamosus.
Mariopteris sphenopteroides.
Mariopteris nervosa.
Mariopteris incompleta.
Mariopteris occidentalis.
Pecopteris vestita.
Neuropteris ovata.
Neuropteris rarinervis.
Neuropteris scheuchzeri.
Odontopteris bradleyi.

Fossil plants (lot 2737) from center of sec. 13, T. 11 N., R. 23 E., Sallisaw (Ind. T.) quadrangle.

Annuluria stellata.
Annularia sphenophylloides.
Sphenophyllum emarginatum.
Sphenophyllum fasciculatum.
Sphenophyllum cf. thoni.
Mariopteris sphenopteroides.
Mariopteris occidentalis.
Mariopteris incompleta.
Sphenopteris pinnatifida.
Sphenopteris mixta.
Sphenopteris cf. cristata?.
Pecopteris vestita?.
Pecopteris robusta?.
Alethopteris ambigua.
Callipteridium sullivantii.
Neuropteris missouriensis.
Neuropteris scheuchzeri.
Linopteris cf. münsteri.
Cordaianthus ovatus.

OTHER COLLECTIONS.

The following localities are represented by collections too small and of too little value to deserve formal consideration from a correlative standpoint, especially in a case like the present, where the expansion of the formations is so great as to show but little floral change in an interval of hundreds of feet.

The first of these lots, from shale just above the quarry at the Catholic church, may belong to the Coal Ridge or Van Buren stage.

Fossil plants (lot S) from sec. 2, T. 7 N., R. 25 W.

Pecopteris vestita.
Pecopteris oreopteridia.
Cardiocarpon branneri.
Cardiocarpon cf. circulare.

Fossil plants (lot J) from sec. 31, T. 7 N., R. 28 W.

Neuropteris missouriensis.

Fossil plants (lot R) from Caulk's pit, east of Caulksville.

Alethopteris serlii.
Linopteris sp.

Fossil plants (lot A) from sec. 16, T. 9 N., R. 22 W.

Neuropteris missouriensis.
Mariopteris occidentalis.
Mariopteris sp.

REPORT ON MARINE CARBONIFEROUS FOSSILS FROM THE COAL FIELDS OF ARKANSAS.

By George H. Girty.

From Sixmile Creek, south of bridge east of Caulksville.

Aviculipecten whitei.

From No. 1 mine of Consolidated Anthracite Coal Company, Spadra, Ark., in sec. 24, T. 9 N., R. 24 W.

Pleurophorus subcostatus?.

No label.

Pleurophorus subcostatus.
Aviculipecten whitei.

From shale on Little Piney Creek above junction with Big Piney.

Euomphalus catilloides?.

From southeast corner sec. 30, T. 7 N., R. 29 W., in sandstone over coal.

Sedgwickia aff. topekensis.

From Sixmile P. O., in sec. 25, T. 8 N., R. 28 W.

Marginifera muricata.
Composita subtilita.
Edmondia aff. E. subtruncata.
Edmondia? sp.
Leda aff. L. nasuta.
Schizodus? sp.
Astartella varica?
Deltopecten aff. D. occidentalis.
Yoldia aff. Y. carbonaria.
Pleurophorus angulatus.
Euphemus nodicarinatus.
Platyceras aff. P. nebraskense.
Nautilus sp.
Orthoceras sp.
Various small undet. gasteropods.

From south side of Spadra Hill, in sec. 29, T. 9 N., R. 24 W.

Crania? sp.
Aviculipecten whitei.
Aviculipecten sp.
Leda? sp.
Pleurophorus oblongus.
Naticopsis nana.
Naticopsis sp.
Pleurotomaria? sp.
Murchisonia? sp.
Ostracoda.

From southwest corner NW. ¼ NE. ¼ sec. 15, T. 9 N., R. 32 W.

Lophophyllum profundum.
Derbya sp. (not crassa).
Productus sp.
Squamularia perplexa.
Spirifer rockymontanus.
Composita subtilita.
Hustedia mormoni.
Aviculipecten sp.
Myalina perniformis.
Astartella vera.
Nucula ventricosa.
Edmondia aff. E. nebraskensis.
Pleurophorus angulatus.
Macrodon obsoletus.
Patellostium? sp.
Orthoceras sp.

From NW. ¼ sec. 15, T. 9 N., R. 32 W., 3 miles northwest of Van Buren.

Crinoidal.
Lophophyllum profundum.
Composita subtilita.
Pleurophorus angulatus.
Soleniscus klipparti.
Pleurotomaria sp.

From road 50 paces south of railroad, in sec. 9, T. 9 N., R. 31 W. (C. D. S).

Crinoidal.
Prismopora sp.
Rhombopora sp.
Derbya sp. (not crassa).
Marginifera muricata.
Composita subtilita.
Dielasma? sp.
Spirifer rockymontanus.
Hustedia mormoni.
Macrodon obsoletus.
Deltopecten occidentalis.
Schizodus sp.
Pleurophorus immaturus?
Naticopsis sp.
Pleurotomaria sp.

From vicinity of Plymouth, Ark., on road 100 paces north of town, in NW. ¼ sec. 35 T. 11 N., R. 29 W.

Michelinia sp.
Polypora ? sp.
Fistulipora ? sp.
Derbya sp. (not crassa).
Marginifera ingrata?.
Spirifer rockymontanus.
Composita subtilita.
Hustedia mormoni.
Macrodon obsoletus?.
Leda aff. L. nasuta.
Astartella concentrica Conrad.
Euomphalus catilloides.
Euphemus nodicarinatus.
Nautilus sp.

From W. ½ sec. 35, T. 9 N., R. 28 W., just south of hill.

Marginifera muricata.
Hustedia mormoni
Derbya crassa?.
Composita subtilita.
Avicula acosta?.
Lima retifera?.
Aviculipecten sp. *a*.
Nucula ventricosa.
Leda sp.
Astartella ? sp.
Pteria ohioensis?
Astartella concentrica Conrad.
Pleurotomaria aff. brazoensis.

From one-fourth mile north of Burma station, on Frisco Railroad, Woodson's strip pit, sec. 19, T. 5 N., R. 31 W.

Naiadites elongatus.
Allerisma ? sp.

From near southwest corner of sec. 15, T. 9 N., R. 32 W.

Monilipora sp.
Crinoidal.
Lophophyllum profundum.
Rhombopora sp.
Spirifer sp.
Spirifer rockymontanus.
Spirifer cameratus.
Spiriferina kentuckyensis?.
Composita subtilita.
Dielasma sp.
Deltopecten occidentalis.
Deltopecten aff. D. texanum.
Aviculipecten sp. *a*.
Nucula ventricosa?.
Astartella varica.
Schizodus sp.
Modiola aff. M. subelliptica.
Euomphalus catilloides.
Bellerophon sp.
Loxonema ? sp.
Griffithides sp. *a*.

From mine of Union Coal Company, west of Paris, Ark.

Aviculipecten whitei.
Pleurophorus subcostatus.

From point 3 miles northeast of Fort Smith, Ark., on Wilson farm, in sec. 1, T. 8 N., R. 32 W.

Marginifera ? sp.
Spirifer rockymontanus.
Spiriferina kentuckyensis.
Composita subtilita.

From west end of Poteau Mountain, Indian Territory, 2½ miles northwest of Coaldale, Ark.

Lophophyllum profundum.
Crinoidal fragments.
Stenopora ? sp.
Fistulipora sp.
Rhombopora lepidodendroides.
Septopora biserialis.
Lingulidiscina aff. L. convexa.
Derbya crassa.
Productus cora.
Productus cf. P. nebraskensis.
Marginifera ingrata.
Spirifer rockymontanus.
Spirifer cameratus.
Spiriferina kentuckyensis.
Composita subtilita.
Hustedia mormoni.
Pugnax osagensis.
Dielasma bovidens?.
Aviculipecten aff. A. coxanus.
Aviculipecten germanus.
Lima retifera?.
Pteria ohioensis?.
Pseudomonotis ? sp.
Leda bellistriata.
Myalina aff. M. perniformis.
Solenomya sp.
Schizodus affinis?.
Allerisma terminale?.
Parallelodon tenuistriatus.
Cypricardinia carbonaria.
Astartella concentrica?.
Astartella varica.
Edmondia mortonana?.
Pleurophorus immaturus?.
Pleurophorus tropidophorus.
Euconospira n. sp.
Pleurotomaria aff. P. tenuicincta.
Pleurotomaria aff. P. subconstricta.
Pleurotomaria aff. P. giffordi.
Patellostium marcouanum.
Bellerophon harrodi?.
Aclis stevensana.
Sphærodoma sp.
Orthoceras cribrosum?.
Nautilus sp.
Phillipsia cliftonensis?.

From west end of Poteau Mountain, Indian Territory, 2½ miles northwest of Coaldale, Ark., at point 150 feet above shale fossils.

Deltopecten occidentalis?.
Myalina perattenuata.
Myalina aviculoides.
Aviculipinna americana.
Allerisma terminale.
Schizodus compressus.
Pleurophorus sp.

All these fossils are of Pennsylvanian age, and all show closely related faunal facies. I regard them as rather low in the Pennsylvanian. Very little discrimination can be made between these collections on the strength of their invertebrate faunas. Those from the black shale associated with coal beds have to a certain extent an individual aspect, owing to their limited variety, a fact which I ascribe to impure or brackish water conditions, but even these are related to the more varied and more obviously marine assemblages of species.

The lot collected near Sixmile post-office, in sec. 25, T. 8 N., R. 28 W., which represents, I believe, the highest horizon in the collection from Arkansas, has to a limited extent peculiarities that differentiate it from some of the other collections coming from lower beds. One fact in point is the relatively restricted representation of brachiopods, which group is more abundant in some of the other lots. The pelecypods are largely the same. It is very doubtful, however, whether this difference (the brachiopod representation) should be given any stratigraphic significance. It may be local or accidental. Other collections from the same horizon at somewhat separated points would be necessary to determine this fact.

Lithologically the collections from shale on the west end of Poteau Mountain in Indian Territory are distinct from the others; and though a good many species are common to both series of collections, I believe the Poteau Mountain material to represent a younger horizon. This is perhaps especially true of the collection obtained from 150 feet above the shale fauna. The latter can possibly be correlated with the Flint Ridge horizon of Ohio.

STRUCTURE.

GENERAL FEATURES.

The coal field of Arkansas lies in a long, comparatively narrow synclinal trough extending eastward along Arkansas River valley from the Indian Territory line. North and south of the field the coal-bearing strata have been eroded, leaving only barren rocks of the Atoka and Winslow formations exposed. This trough lies between the Boston Mountains on the north and the Ouachita Mountains on the south, two elevated land masses which have very different geologic structures. The Ouachita region is characterized by long, sharp ridges formed by the erosion of alternating hard and soft beds dipping at high angles. They are in fact strike ridges of upturned rocks. The various strata comprising this mass have been subjected to violent strains and compressed in a north-south direction, throwing them into folds whose axes extend approximately east and west. Subsequent to this crumpling the upper parts of the folds have been eroded, leaving the edges of the harder beds projecting in ridges as we now find them. In the process of folding the strata were here and there broken and in many places the beds slipped out of position so that their outcrops are not now continuous for very great distances. Such fractures are called faults by geologists. As a general rule, the faults of the Ouachita Mountain province are of the kind that is produced by compression. In such faults the fracture plane is, as a rule, inclined, and the beds on the upper side have slipped over those on the lower side—in fact, are thrust over them—and for this reason such displacements are called thrust faults. In general the faults of the Ouachita Mountain region extend approximately east and west parallel with the trend of the ridges.[a]

The rocks of the Boston Mountain province[b] are not so intensely folded as those of the Ouachita province, but are, as a rule, only slightly distorted from their original horizontal positions. They are characterized by low dips, seldom exceeding 4° or 5°. This mass appears to have been raised up like a great block of the earth's crust, allowing the lowlands of Arkansas Valley to break away from it. Where one part of the earth's crust is raised up higher than an adjoining part, the beds at the two levels must either bend or break. A flexure produced in this way is described as a monocline or monoclinal fold. Fractures or faults thus produced differ in type from those found in the Ouachita Mountains in that they occur in beds not crumpled by lateral pressure and otherwise little disturbed from their original positions. Usually in such faults the plane of fracture does not stand exactly vertical, and the beds on the upper or hanging-wall side slip down, while those on the lower or foot-wall side rise. Faults of this kind are described as normal, drop, or tension faults. They are characteristic of the geologic structure of the Boston Mountains, and a series of them, extending approximately east and west, occurs along the north side of Arkansas Valley, and in many places separates the Boston Mountain province from the coal field.

---

[a] For a description of the geologic structure of the Ouachita Mountains, see Taff, Joseph A., Atoka folio (No. 79), pp. 6 and 7; Coalgate folio (No. 74), p. 5; and manuscripts of McAlester, Windingstair, and Tuskahoma folios, not yet published.

[b] Purdue, A. H., Winslow folio. (In preparation.)

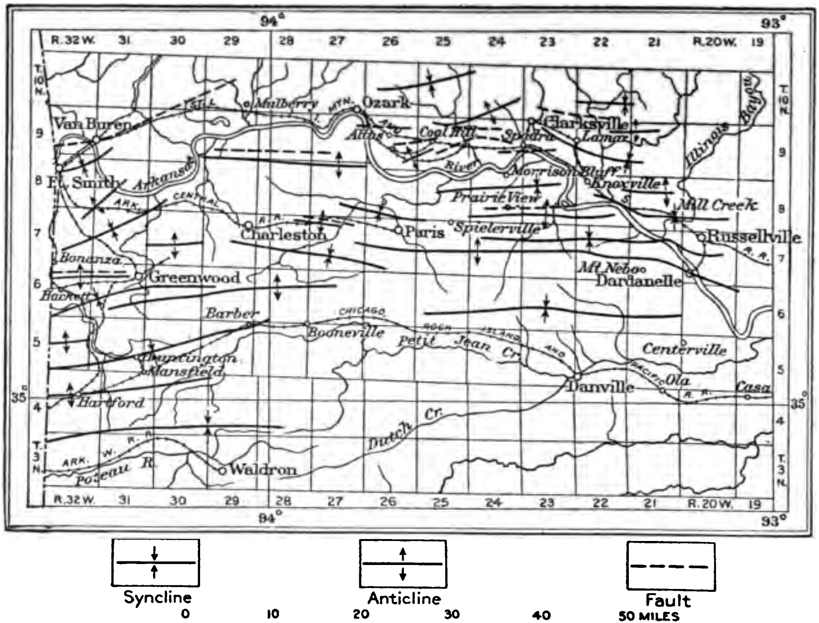


FIG. 8.—Map showing structural features of Arkansas coal field.

It will be seen from this description that the Arkansas Valley syncline, which contains the coal field, is peculiar in that on its south side the underlying rocks rise by pronounced folds and thrust faults, while on the north side the underlying rocks are brought to the surface by a simple monoclinal uplift, accompanied at some places by normal *faulting.*

The structures within the coal field partake of the nature of both these types, since the rocks are definitely folded at many places along the southern edge of the field, while near the northern edge the dips are gentle, the beds lie nearly flat, and normal faults are of frequent occurrence. The principal structural features of the field are shown in fig. 8.

ANTICLINES.

Although the coal field in general has been described as a synclinal trough, it is folded into a number of minor synclines and anticlines. The determination of these features is of great importance to the miner and coal prospector, since without a knowledge of this structure it is impossible to determine the best methods of prospecting and working the coal. Generally the largest areas of coal land are in the synclines, and where the structure is of this type the bed is at its greatest depth in the axis of the fold. The coal bed is most easily prospected around the margins of such basins, but in mining it is usually most economical to locate the main shaft at the deepest place, so that the loaded cars can be moved to it by gravity. Where the coal beds lie deep, however, the value to the prospector of recognizing the anticlinal structure is of almost equal importance, for it is in the anticlines that he must expect to find the coal for which he is searching nearest to the surface. In general the minor anticlines and synclines of the Arkansas coal field have approximately east and west axes only a few miles in length.

Backbone anticline.—Probably the best known anticline in the whole district is that in Backbone Ridge, between Bonanza and Hackett, which extends from the State line eastward for about 7 miles. The coal-bearing beds that outcrop on the north and south sides of this ridge are tilted at high angles, and in its axis rocks lying far below the coal horizons are exposed. (See fig. 9.) This anticline is an unsymmetrical fold resembling the Ouachita Mountain type, and represents a thrust of the rocks from the south over those on the north side of the ridge. The strata are broken along its axis and a well-marked thrust fault, which at the Indian Territory boundary has a displacement of over 2,000 feet, has been traced nearly to Greenwood, 7 miles to the east. The area of marked folding also ends here.

Biswell Hill anticline.—Biswell Hill, an elliptical domelike eminence northeast of Greenwood, which is mantled over by the Hartshorne sandstone, is the topographic expression of a broad anticline whose axis is parallel with and a short distance northeast of the east end of the Backbone Ridge anticline. The fold is slightly unsymmetrical in that the dips to the north are higher than those to the south. Like the Backbone Ridge anticline, it marks a barren area surrounded by the outcrops of the Hartshorne coal, which dips away from it to the north and south. The structure, however, is apparently favorable for the accummulation of natural gas.

Massard Prairie anticline.—Another anticline, which is of considerable economic importance, since it has been successfully exploited for natural gas, is that at Massard Prairie, 5 miles southeast of Fort Smith. The surface indications here suggest a broad elliptical uplift with low dips to both the north and the south. The many drill holes in the axis of this fold indicate a barren area surrounded by the outcrop of the Hartshorne coal.

Montreal anticline.—Another anticline of some importance in coal mining is one which extends west from Montreal, in the southern part of Sebastian County, to the State line. This is a very broad fold, but it serves to bring the Hartshorne coal horizon nearer the surface than it is in the region north and south of it.

Hartford anticline.—The Hartford anticline, a broad fold whose axis extends for several miles in a northeast-southwest direction, is of great economic importance, since it brings the coal horizon within easy reach from the surface. At Coops Prairie, northeast of Hartford, this fold assumes a domelike structure almost ideal for the accumulation of natural gas. The wells located here supply the gas used at Huntington and at the Mansfield brick factories.

Mill Creek Ridge anticline.—East of Greenwood the coal field narrows down to a width not exceeding 15 miles, and in this strip there is at many places only one simple syncline from the south side of the coal field to the north. It comprises, however, a few minor anticlines which are worthy of mention. One of these is the Mill Creek Ridge, which extends from Arbuckle Island, in Sebastian County, to Roseville, in Franklin County. This ridge belongs rather to the northern edge of the coal field, from which it is not wholly disconnected. It is a broad, open fold characterized by low-dipping rocks. Since the rock which mantles this fold is for the most part Hartshorne sandstone, it can not be regarded as coal land, though its southern boundary marks the edge of the coal fields.

Game Hill anticline.—There is also a small, short, elliptical anticline in Logan County, extending westward from Caulksville to Branch, which is worthy of examination, since it brings the Hartshorne horizon within a few hundred feet of the surface. There is also some evidence here of a fault, which will be described later.

Prairie View anticline.—The Prairie View anticline, about 10 miles east of Paris, appears to be a broad, open fold, but of sufficient magnitude to bring up the Hartshorne sandstone and Atoka shale, leaving a barren area in the center. The folding here is rather pronounced, and there is an east and west fault along the axis. It is not known whether it is of the thrust or normal type, though its association with the fold and the fact that the downthrow is on the north side suggests that it is a thrust fault.

Coal Hill anticline.—The Coal Hill anticline is a broad fold with east and west axis and low dips to both the north and the south. (See fig. 22.) It is of considerable economic importance, since it forms a barren area in the heart of the Coal Hill-Denning field, and will be described further in connection with the coal beds.

Russellville anticline.—The Russellville anticline is a very broad, dome-shaped uplift, with indefinite axis, between the Ouita and Shinn coal basins. It is surrounded by the outcrop of the Hartshorne sandstone.

SYNCLINES.

The synclines of the Arkansas coal field, especially near the southern edge of the field, are apt to be unsymmetrical, the beds on the south side having a higher dip than those on the north. Many of the synclines which occur near the north side of the coal field are faulted, so that only a part of the original fold is left. In general the more valuable coal deposits occur where the structure is synclinal.

Fort Smith syncline.—In the heart of the syncline beneath Fort Smith the Hartshorne coal horizon lies at a depth of 700 to 800 feet. This is a very broad fold, with rather indefinite axis. The strata dip northward from Massard Prairie at a low angle to the northern limit of the city, beyond which the dips are to the south.

Central syncline.—Another syncline of greater importance extends from the town of Central, in Sebastian County, southwestward to the State boundary. This also is a very broad and shallow trough, in the deepest part of which the Hartshorne horizon is probably not more than 800 feet below the surface.

Greenwood syncline.—South of Greenwood there is a more extensive trough of this kind, which extends from the boundary line at Hackett northeastward past Greenwood for about 30 miles. At its deepest point in this trough, south of Hackett, the coal horizon does not exceed 800 feet below the surface. At Greenwood the depth of the coal is not beyond 600 feet, while at Potato Hill, a prominent butte a few miles east of Auburn, the coal horizon is at a depth not less than 1,400 feet.

Sugarloaf syncline.—The next important syncline south of the Greenwood syncline may be described as the Sugarloaf syncline, since it includes the two peaks of Sugarloaf Mountain. It is an important coal basin, containing large areas where the coal is within easy reach from the surface, though the depth of the coal horizon below the top of the eastern peak of Sugarloaf Mountain is about 2,000 feet. East of Huntington this syncline has no economic importance, since the rocks exposed are below the coal horizon.

Poteau syncline.—Poteau and Whiteoak mountains mark the axis *of a syncline in the center* of which the coal horizon must be at great depth, since the rocks exposed on the surface all have comparatively high dips.

Paris syncline.—In the central part of the field there is a broad and very deep syncline underlying the town of Paris, at which place the depth of the Hartshorne coal horizon is about 1,200 feet. This basin is unsymmetrical in that the rocks at the southern edge stand vertical and are sometimes slightly overturned, while those at the northern edge have only very gentle dips. East of Paris the syncline is constricted to a comparatively narrow trough, which extends eastward for several miles south of the Prairie View anticline.

Prairie View syncline.—The Prairie View syncline is a broad basin, with east-west axis, including the Prairie View coal field. Its structure is shown in fig. 24, and it will be further described in connection with the coal beds.

Cabin Creek syncline.—The Cabin Creek syncline is a very broad basin, whose longer axis extends from Clarksville southeastward nearly to Knoxville. The dips, both north and south, are low and practically symmetrical. In its axis the Hartshorne coal horizon is from 600 to 700 feet below the surface.

London basin.—Near its east end the coal field narrows down to a single broad synclinal basin with rather indefinite axis, which may be described as the London basin. This syncline lies between the ends of the Prairie View and Russellville anticlines, and its structure is not well known, for the surface is largely covered with alluvial deposits. The Hartshorne coal horizon is probably 600 to 800 feet below the surface in its deepest part.

Ouita and Shinn basins.—The London basin apparently divides at its west end, one limb passing north of the Russellville anticline, where it is known as the Ouita basin, the other, which passes south of Russellville, being the Shinn basin.

The Ouita basin is a shallow flexure from which the coal-bearing rocks extend westward in depth and are continuous with those of the London basin.

The Shinn basin is a comparatively sharp fold carrying the coal horizon to a depth of 600 feet. The coal-bearing rocks, however, are not connected with those of the London basin, an area of barren rocks intervening.

FAULTS.

General types.—The term fault, in the geologic sense, is applied only to a break or fracture of the earth's crust along which there has been some displacement of the rocks. It is often used by coal miners and operators in Arkansas to signify original defects in the coal, marked by unusually thin places, places showing many partings, or other conditions due to causes that prevailed at the time of its deposition.

It has already been shown that the Arkansas coal field exhibits both normal and thrust faults, whereby the rocks making up the coal-bearing series and comprising a part of the earth's crust have been broken and displaced. (See figs. 9 and 10.) Where a fault is encountered in the mines the coal bed is usually cut off abruptly, and it often requires much labor and great expense to find it again. Indeed, many mines have been abandoned for this cause, and the economic importance to the mine operator of a thorough understanding of the nature of the faults in his particular field is very great. Within this coal field eleven faults of large proportions and a number of smaller unimportant ones are known to occur, and it is probable that there are other faults which were not recognized in this rather rapid reconnaissance. It is not believed, however, that any faults affecting the more important parts of the district have been overlooked. The recognition of features of this kind in a region like the Arkansas coal field, where all the rocks are similar, is very difficult, and it has often been practically impossible to locate them with the accuracy desired. Therefore the position of many of the faults shown on the map must be regarded as only approximate.

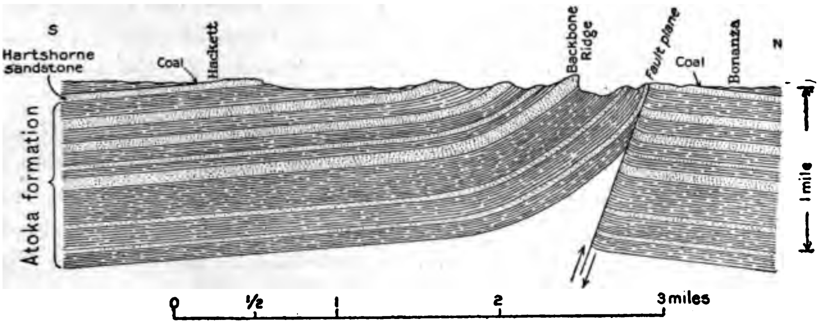


FIG. 9.—Diagram of Backbone Ridge fault.

Backbone Ridge fault.—The best known fault in the district is that along the axis of Backbone Ridge. (See fig. 9.) This displacement was recognized by the geologists of the Arkansas Survey and is represented on the geologic map published in the preliminary report on the coal field.[a] Its western end in Indian Territory has been located by J. A. Taff.[b]

The fault extends from the boundary eastward for about 8 miles to a point a mile northwest of Greenwood. Measurements during the past season indicate that the displacement is approximately 5,000 feet near the Indian Territory line. The fault occurs in barren rocks and does not affect the economic development of the field.

---

[a] Ann. Rept. Geol. Survey Arkansas for 1888, vol. 3, map of coal field (in pocket), Little Rock Press Printing Co., 1888. Winslow, Arthur, Geology of western Arkansas: Bull. Geol. Soc. America, vol. 2, 1891, fig. 4, p. 229.

[b] Taff, Jos. A., geology of the eastern Choctaw coal field: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 2, 1900, p. 285.

Devils Backbone Ridge and Pine Ridge faults.[a]—Faults of similar character probably also occur in some places along the southern boundary of the coal field, in what is known as the Devils Backbone Ridge at Chismville and as Pine Ridge farther east. For several miles along this ridge, which is composed of the Hartshorne sandstone, the beds are slightly overturned and the rocks on the south side are very much crumpled and at places broken. Although the evidence has not been worked out in the same detail for this area as for Backbone Ridge, there seems little doubt that thrust faulting has occurred, producing a certain amount of displacement.

Caulksville fault.—There is probably also a small fault, with a downthrow of 50 or 60 feet on the north side, extending from a point near Caulksville to Branch. This fault would run through the prairie between Game Hill and Rocky Hill. It is probably of very little economic importance, and would not interfere seriously with mining operations.

Prairie View fault.—The Prairie View fault, which has already been mentioned in connection with the Prairie View anticline, extends from sec. 25, T. 8 N., R. 25 W., eastward for about 7 miles to Arkansas River. The downthrow is to the north and the displacement is not less than 500 feet. This fault cuts off and defines the southern limit of what is called the Prairie View coal field. The evidences of disturbance here shown by drill records and surface geology are very conclusive, but there is nothing to show the character of the fault, though its association with moderate folds and its proximity to Pine Ridge, which marks a well-developed fold, would suggest that it is due to overthrust.

Faults which occur along the northern edge of the coal field are much more difficult to discover; the evidence regarding their existence is obscure, and they are very troublesome to the geologist who attempts to interpret the structure of the coal field. They are, however, much more troublesome and have been a source of great expense to those who have attempted to operate coal mines in this region. These faults are all of normal type; they are not accompanied by folds, and most of them extend in an approximately east-west direction. At their extremities the displacement gradually grows less and disappears, so that the beds can be traced continuously around the ends. In some of these faults, however, sandstone beds are brought against other sandstones, shales against shales, so that it is only by the most careful study that the displacement can be recognized or its nature determined.

Clarksville fault.—One of the first of these faults discovered during the work here reported extends from a point a few miles south of

---

[a] Winslow, Arthur, op. cit., fig. 3, p. 228.

Lutherville westward for about 15 miles, and probably dies out a mile or so northwest of Clarksville. Through this distance the exact line of the fault could not be located with certainty in the time available. A few miles east of Clarksville sandstone belonging to the Fort Smith formation is dropped down and brought into contact with the Hartshorne sandstone, showing that the displacement is not less than 500 feet. (See fig. 10.) At the contact the two sandstone beds are not easily distinguishable, and in making a circuit northeastward from Clarksville across this fault, thence west for a few miles, and then south, the geologist is bewildered by finding that the sandstone which he must believe is still in the Fort Smith formation dips under the Spadra shale.

North of this fault the rocks below the coal horizon are raised and the coal-bearing rocks washed away except in small local basins. The economic importance of the fault, therefore, is very great.

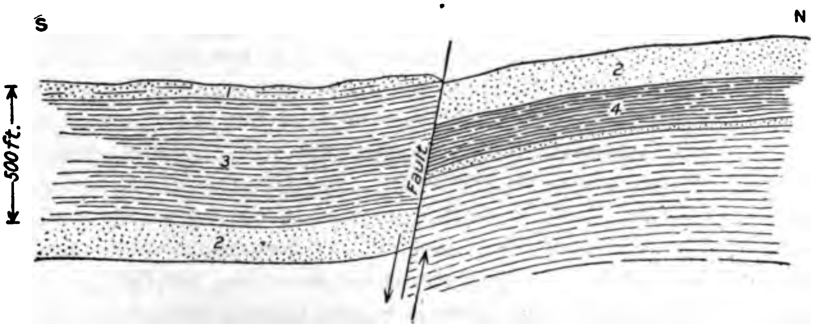


FIG. 10.—Diagram of Clarksville fault at a point 2½ miles east of Clarksville, illustrating type of faulting common in the northern part of the coal field. 1, Fort Smith formation; 2, Hartshorne sandstone; 3, Spadra shale; 4, Atoka formation.

Big Danger fault.—Another fault which lies south of Clarksville and affects the value of the Spadra coal field will be called the Big Danger fault from the fact that the best surficial evidence of the existence of a fault is found at the south base of Big Danger Hill, in sec. 23, T. 9 N., R. 23 W. From that point the fault extends westward for a total distance of 10 miles. From Spadra west it is parallel with and about a quarter of a mile south of the line of the Iron Mountain Railway. It is a normal fault, with the downthrow on the south side. The amount of displacement is indicated by a drill hole to be about 270 feet opposite the mouth of Spadra Creek and about 300 feet at the east end of Spadra Hill. West of that point the displacement probably decreases gradually and dies out near the west end of Spadra Hill. The economic importance of this fault is very great, since south of it the Spadra coal bed has been dropped down so far that it has not yet been mined.

Spadra fault.—The name Spadra is applied to a fault which was first encountered in one of the mines in the Spadra field. It was afterwards located by a series of drill holes at a point a mile or two farther west, and its presence a short distance east of Hartman is indicated by the results of drilling. Its extension from Hartman in a southwesterly direction is based wholly on a study of the outcrops. The evidence is as follows: A pronounced escarpment extending southwestward from Hartman for a distance of about 4 miles marks the boundary of the river bottom lands. Bed-rock exposures along this scarp are favorable for study, and since a branch of the Iron Mountain Railway follows its base, indications of disturbance are to be seen at many places. The occurrence of the coal bed, as well as the surface distribution of the various other formations as far as they are known, can hardly be accounted for on any other hypothesis than that the Spadra fault follows the line of this escarpment after passing Hartman. This is a normal fault with downthrow to the south, the coal bed being raised on the north side. At its eastern end, where the fault was first encountered in one of the mines, the displacement is only a few feet, and, although it is reported to have caused great consternation at first, the coal was soon located again on the other side, and there was very little loss. It has not been encountered elsewhere in the mines, for the reason that none of them have extended their workings so as to cross the supposed line of the fault. About 2 miles east of Hartman the displacement, as indicated by a reported drill hole, is not less than 200 feet.

The recognition of this fault is of the utmost importance in the economic development of the Spadra field, since it indicates the possibility of coal in a large area south of Hartman, heretofore regarded as barren.

Hartman fault.—A fault extends from a point in sec. 14, T. 9 N., R. 25 W., about 1 mile north of Hartman, in an east-northeast direction through sec. 10, T. 9 N., R. 24 W., for a distance of 4 miles. It differs from the two faults just described in that the downthrow is on the north side. The fault was first encountered in the workings of the old Allen[a] slope about 1½ miles northeast of Hartman. It is reported that at this place the coal was followed down a slope to the south until the bed ended abruptly against a wall of sandstone. Although the mine has been abandoned for many years, the surface indications verify this report. The fault is traceable from the old mine westward across Horsehead Creek to a point north of Hartman, where a sandstone, presumably the Hartshorne, has been followed continuously around its western end. East of the old Allen mine the exact position of the fault could not be located nor its extent determined from the surface geology. The amount of displacement at the point of original discovery is about 200 feet. The effect of this fault is to raise a part of the Hartshorne sandstone and Atoka shale south of the Allen mine and to produce a tongue of barren ground which extends from Hartman northeastward into the heart of the Spadra field.

---

[a] Ann. Rept. Geol. Survey Arkansas, vol. 3, 1888, p. 23.

Coal Hill fault.—The Coal Hill fault extends westward from a point 1½ miles east of the town of Coal Hill to a point about midway between the towns of Altus and Denning. It is of the same type as the Spadra fault; the downthrow is on the south side and the maximum amount of displacement is not less than 200 feet. The effect of the fault is to bring the shale which underlies the Hartshorne sandstone in contact with the Spadra shale. Anyone examining this field casually would be justified in the opinion that the coal bed mined between Coal Hill and Denning extends northward and passes under the Pond Creek Hills. The existence of this fault is indicated by the evident displacement of sandstone beds which are found to be identical at its ends. It is also proved by numerous drill holes within the coal field. A rather remarkable and significant condition in this field is that the workings of the various mines between Coal Hill and Denning all lie south of a rather definite east and west line, although there is no topographic or other evidence of the discontinuance of the coal bed to be seen on the surface. It is generally reported that the coal bed is divided by a thick shale parting near the fault, so that the workings are usually abandoned before the actual break is reached. In a few of the mines, however, the fault has been actually observed, though at present none of the workings which approach it are accessible. In one or two instances where the fault plane was reached the coal bed is reported to be dragged upward slightly, indicating the direction of the movement.

Altus fault.—A fault believed to pass through the town of Altus also extends in an east and west direction. Its existence is inferred from the distribution of geologic formations on the surface, although its exact location was not determined at any point on the ground. The Hartshorne sandstone, which mantles the hill south of Altus at an elevation of about 600 feet, is raised by this fault so that it also caps Catholic Hill, north of the town, at an elevation of 900 feet. This fault is of the same type as the Coal Hill fault, with which it is parallel, and it probably takes up the displacement where the latter dies out.

Mill Creek fault.—The Mill Creek fault apparently extends from Arkansas River at Arbuckle Island eastward to sec. 24, T. 9 N., R. 28 W. Mill Creek, which flows nearly due west from the latter point, follows a valley whose position is determined by the fault. The downthrow of this fault is to the north, and in this respect it differs from most of the faults of the northern part of the coal field.

The total amount of displacement, which can be easily measured, since the Hartshorne sandstone caps the hills on both sides of Mill Creek valley, probably does not exceed 200 feet at any point. This fault has little economic significance, since it is not believed that any coal beds large enough to work are affected by it.

Massard fault.—There is evidence of a fault near the mouth of Massard Creek about 7 miles southeast of Fort Smith. Its direction and linear extent could not be determined on account of imperfect geologic exposures, though at the point mentioned a lower bed of the Fort Smith formation is dropped down and brought in contact with the Hartshorne sandstone, thus indicating a displacement of at least 400 feet. In this case the downthrow is on the south side, like most of the northern faults. The course of the fault seems to be approximately northeast and southwest. Although the fault could not be located for more than a quarter of a mile there are some indications of disturbance in Massard Prairie southeast of the gas wells in sec. 1, T. 7 N., R. 32 W., and at the Indian Territory boundary 1 mile southwest of Cavanaugh. These conditions would be explained by the continuance of this fault from the mouth of Massard Creek southwestward through Massard Prairie and thence westward to the Indian Territory line. The evidence at hand for such a fault, however, can not be regarded as in any way conclusive, and the proximity of the gas wells on Massard Prairie seems to be prima facie evidence against the existence of a fault in the position mentioned. The position of the Massard fault can be proved only by systematic drilling, and therefore it has not been indicated on the geologic map except for a short distance at the mouth of Massard Creek.

Mulberry fault.—One of the most extensive faults or systems of faults recognized in the coal field extends from a point a few miles north of the town of Mulberry[a] southwestward past the town of Van Buren and for a distance of about 15 miles into Indian Territory.[b] The east end of this fault near Mulberry has already been mapped by Purdue, since it extends into the area covered by the Winslow quadrangle. At this point the evidence regarding the existence of a fault seems to be conclusive. Its course westward is marked through a considerable part of the distance by a prominent escarpment. For several miles between Alma and Van Buren the evidence of the existence of a fault is not conclusive, and it is possible that the movement is taken up in a monoclinal fold. The possible position of the fault is indicated by dotted lines. At the town of Van Buren the amount of the displacement can not be less than 300 feet, while it may be as great as 1,000 feet. At this place the soft shaly sandstone and shale of the coal-bearing rocks are brought in contact with some of the lower shale of the Winslow formation, and on superficial examination the conclusion would be justified that the coal-bearing rocks continue northward, passing under the Van Buren Hills.

---

[a] Purdue, A. H., Winslow folio, No. —, U. S. Geol. Survey. (In preparation.)

[b] Taff, Joseph A., Sallisaw folio, U. S. Geol. Survey. (In preparation.)

This fault has a number of economic bearings. First, it limits the area of the coal-bearing rocks on the north. Although it is not known that the rocks of this group here carry any coal beds of commercial value, it is possible that valuable coal beds may be found in them. Second, the people of Fort Smith and Van Buren have been accustomed to regard those towns as lying in the center of a synclinal trough, and to believe that the Winslow sandstone dips under them from the Boston Mountains. If penetrated by deep wells these rocks could therefore be expected to yield a flow of good artesian water in place of the present unsatisfactory supply. The existence of a fault here is an unfortunate thing for this hope, since it is hardly conceivable that artesian water would pass across it. A number of deep wells which have been drilled near Fort Smith have failed to produce artesian water, and this failure may well be accounted for by the presence of the fault.

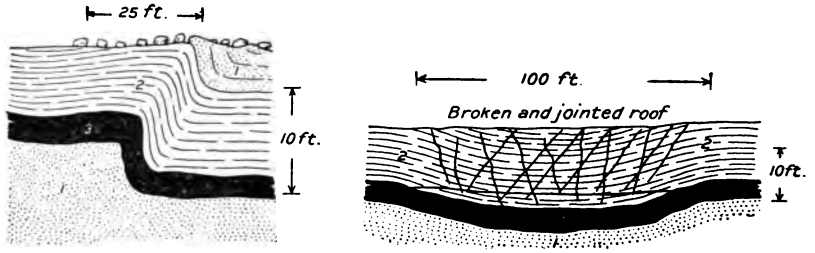
MINOR STRUCTURAL FEATURES.

Joints.—Nearly all the harder rocks, especially the thin beds of hard sandstone included in the shale, show on weathering a system of jointing characteristic of this field. The prevailing joints, which are developed with great regularity, are nearly vertical and invariably strike a few degrees west of north, regardless of other more dominant structures. Secondary irregular joints extend at right angles to these, and the two sets often give thin flat-lying sandstone beds the appearance of artificially laid paving stones. The intervals between the joints of the prevailing system vary from 2 or 3 inches to several feet, and advantage is taken of the joints in quarrying the rock, as shown in Pl. IV, *B*. This jointing is best developed in thin, regularly bedded sandstones and harder shales. It is somewhat irregular and obscure in the more massive cross-bedded sandstones, and can not be recognized at all in the softer shales. The coal beds generally do not show it, even though it may be very well developed in sandstone beds a short distance above or below. In some places where coal beds have sandstone roofs or floors the regular joints are confined to these rocks where they are well developed and do not extend into the coal. Nearly all the coal beds have a somewhat irregular vertical cleavage.

The average strike of the prevailing joints in the west end of the coal field is 15° west of north, while in the east end it is 5° west of north, and in other parts it is intermediate between these two directions. In any given locality the variations in direction are so small as to be difficult of detection even with a pocket compass, and, indeed, the joints are nearly as reliable for giving direction as such an instrument. In one instance which came under the writer's observation they were used in place of a sun dial for giving the time of day and were described as the "eleven o'clock marks." In geologic investigations when there is doubt as to whether certain rocks are outcrops or detached bowlders the direction of the prevailing joints will often be sufficient evidence to settle the question.

Miniature folds.—Another structural feature of minor importance very often seen in the coal field consists of small local folds or buckles in some of the beds, especially in the weathered zone near the surface. Such small folds are usually anticlinal in form, and where encountered in mines and strip pits are sometimes called rolls. In a few instances such folds are accompanied by apparent faults, though such occurrences are relatively rare.[a] Usually the zone of disturbance is only a few feet wide, and beyond it the beds affected continue with perfect regularity. In general, it is not believed that the flexures extend far in depth, since they are very common in such exposures as stream banks and road cuts, and are rarely, if ever, met with in deeper mine workings.

M. R. Campbell, while with the U. S. Geological Survey party in the Arkansas field, examined a number of these rolls, and in a recent paper describing them attributes their formation to expansion of the surface rocks due to weathering.[b]



A. B.

FIG. 11.—Minor structural features of coal beds. A, Miniature monocline in coal bed at Woodson's strip pit; B, miniature syncline in mine of Fidelity Fuel Company. 1, Sandstone; 2, shale; 3, coal.

Two such folds affecting coal beds are shown in fig. 11. The fold exposed at Woodson's strip pit (fig. 11, A), near Burma, partakes of the nature of a fault, since the coal bed is noticeably displaced by it. It is in apparent alignment with a small fault exposed in the Branner mine about half a mile away, and may possibly be due to the same cause. The trough in the Fidelity mine (fig. 11, B) is unusual in that the flexure is synclinal.

---

[a] Purdue, A. H., Illustrated note on a miniature overthrust fault and anticline: Jour. Geol., vol. 9, 1901, pp. 341-342.

[b] Campbell, M. R., Rock folds due to weathering: Jour. Geol., vol. 14, No. 8, 1906, pp. 718-721.

In general, the coal-bearing rocks are subject to great local variation in dip, so that, while they are thrown into broad anticlines and synclines that are easily recognized, the limbs of these folds carry minor anticlines and synclines which it is difficult to locate from surface exposures. Where encountered in the mines, such features are often also called rolls, but they are to be distinguished from the more local phenomena described above, since they are due to the same stresses that produced the more dominant structures, and presumably will extend in depth. The best examples of structure of this type, one of which is given in fig. 15 (p. 53), were found in the Bonanza and Jenny Lind district, though they are probably as common in some of the other districts, where opportunities for investigation are not so good.

ECONOMIC GEOLOGY.

THE COAL BEDS.

DISTRIBUTION.

Coal is by far the most important mineral product of this part of Arkansas, though natural gas, shale, and building stone are also utilized. Prospecting has thus far failed to demonstrate the presence of valuable oil-bearing sands.

Coal beds large enough to be worked occur at three horizons or stratigraphic positions in the coal-bearing rocks of Arkansas. These rocks were deposited as sediments on the bottom of a shallow sea or lake, and each layer of sand or shale represents a part of the deposit made at the same time. The coal beds were formed from vegetable matter at times when the water became so shallow as to permit the growth of vegetation over its surface, shutting out the ordinary sediments. Each coal bed, then, may be regarded as representing a part of the actual surface of the earth at some particular time, and coal beds that were formed at the same time, although they may never have been actually connected with each other, are said to belong to the same horizon.

For convenience in discussion the coal beds now to be described will be grouped according to the geologic horizons at or near which they occur, namely, the horizon of the Hartshorne coal, which takes its name from Hartshorne, Ind. T.; that of the Charleston coal, mined for local use near Charleston, Ark., and not known to be represented in Indian Territory; and that of the Paris coal, which in all probability corresponds approximately to the McAlester coal of Indian Territory.

The stratigraphic positions of these horizons are shown in Pl. I. Nearly all the various coals mined in Arkansas can be correlated with one or another of these horizons. There is, however, still some doubt regarding the exact correlation of the Pickartz and Philpott coal beds, which lie north of the main body of the coal field as outlined, and it is possible that one of them may not be represented elsewhere in Arkansas. Small coal beds, some of which have been mined for neighborhood use, are also known to occur locally at many places in rocks which lie below the Hartshorne sandstone, and it is possible that future development will establish the fact that there are small areas of valuable coal at other horizons than those noted.

COALS OF THE HARTSHORNE HORIZON.

CHARACTER AND DISTRIBUTION.

The coal beds which occur at or near the horizon of the Hartshorne coal are economically the most important in both Indian Territory and Arkansas. This horizon is at the contact of the Hartshorne sandstone with the Spadra shale, and in general the coal bed is taken as the line of demarcation between these formations. As actually observed, however, there is from a few inches to 20 or 30 feet of shale or fire clay between the coal bed and the sandstone, a condition due to local variations either in the character of the upper part of the sandstone formation or in the exact position of the coal itself. In many places in its lower part the Spadra shale is somewhat sandy, and contains lenses of hard sandstone, which lie immediately above the coal bed. For this reason the exact contact of the Hartshorne with the Spadra formation is at some places difficult to determine, and it is probable that in some localities where the outcrop of the coal bed could not be found there have been minor errors in mapping. The Hartshorne sandstone, which is usually called "bed rock" in Arkansas, also varies greatly in character and thickness in different parts of the field. While typically a hard rock over 100 feet thick, described in drill sections as granite, in places it contains less than 10 feet of hard rock and in some localities is represented only by sandy shale or by irregular thin lenses of hard sandstone distributed through 15 or 20 feet of sandy shale, making it difficult to recognize except by its stratigraphic position. It has not been identified at all in the northern part of the Indian Territory field.

The extent and distribution of the Hartshorne coal horizon, as represented in the rocks of Arkansas, is seen in the outline map, fig. 12, which shows approximately the extent of the Arkansas coal field. The coal bed is subject to great local variation in thickness and character. Partings come and go without reference to any known rule, and in some parts of the field the coal is entirely absent. Those areas in which there is reason to believe that the coal is sufficiently thick for mining are indicated in fig. 12. The local conditions and variations of this bed are best described under the headings of the various districts in which it is mined.

The area north of Backbone Ridge, in the western end of the field, will be described as one district, since the coal bed throughout this area exhibits a general similarity in character. The region south of Backbone Ridge is best described under several headings on account of the local variations in the coal bed, though the mine workings are almost continuous. The various districts where coal is mined in the eastern end of the field are isolated from one another.

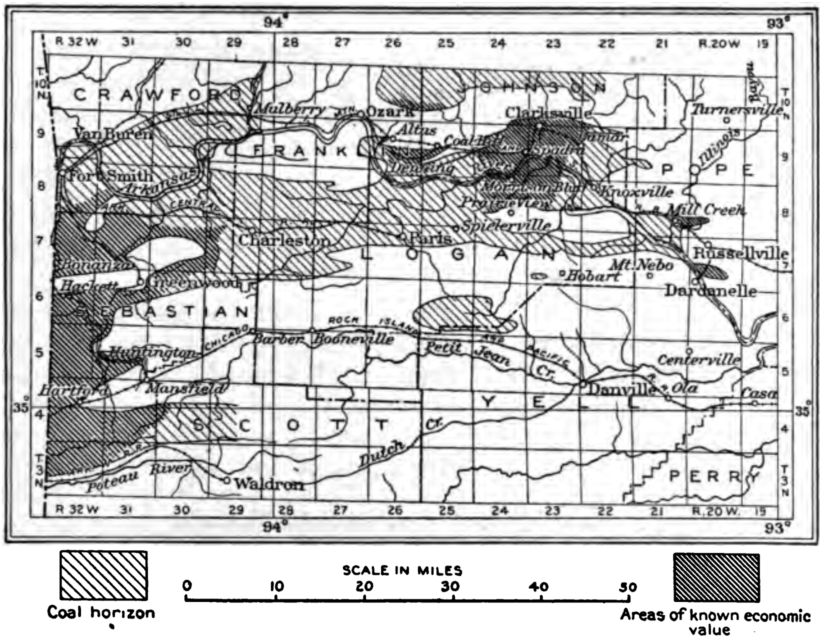


FIG. 12.—Distribution of Hartshorne coal horizon and areas in which the coal is known to be of economic value.

BONANZA AND JENNY LIND DISTRICT.

The district north of Backbone Ridge, in Sebastian County, includes several important mines, which are located along the southern outcrop of the coal bed near the towns of Bonanza and Jenny Lind. The position of the outcrop here is indicated by the Hartshorne sandstone, which is easily traced along the north side of Backbone Ridge and Biswell Hill to Oak Valley, where it turns southward and connects with the sandstone that underlies the coal at Greenwood and Hackett. From its southern outcrop at Jenny Lind the coal dips northward at an average angle of approximately 2½° for about 3 miles, where it is from 600 to 900 feet below the surface. It then rises with a still more gentle slope and outcrops at several points on Massard Prairie, from which it dips northward again and passes under Fort Smith. The areas in which the coal is near the surface in this district are indicated by the extent of Long and Massard prairies. Long Prairie at Jenny Lind is a broad lowland, bounded on the south side by Long Ridge and on the north by Tennessee Ridge, the former being the topographic expression of the Hartshorne sandstone, which underlies the coal, the latter that of the lower member of the Fort Smith formation. The relation of this prairie to the bed-rock structure is shown in the sketch, fig. 13.

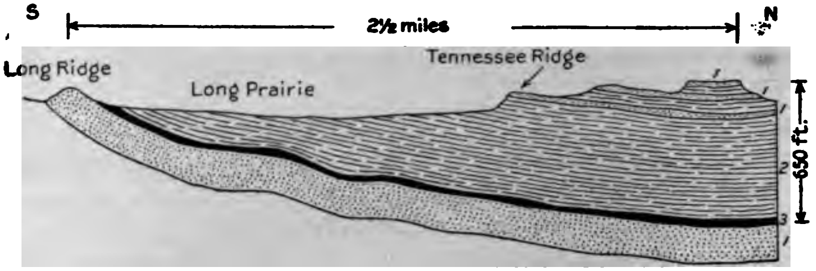


FIG. 13.—Diagram showing relation of topography to geologic structure at Long Prairie near Jenny Lind. 1, Sandstone; 2, shale; 3, coal.

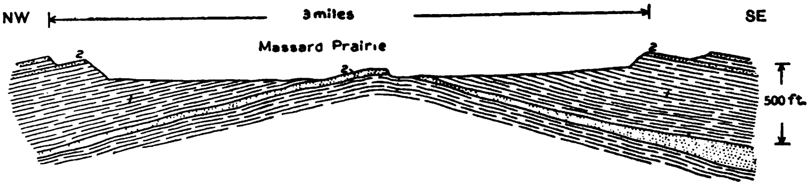


FIG. 14.—Diagram showing relation of topography to geologic structure at Massard Prairie. Section along road from Fort Smith to Greenwood. The gas wells are located in the center. 1, Shale; 2, sandstone.

Massard Prairie is surrounded by the outcrops of a sandstone bed correlated with that of Tennessee Ridge, the relations of topography to bed-rock structure being shown in fig. 14. The coal bed which outcrops in the center of this prairie is probably the same as that at Jenny Lind and Bonanza, though the Hartshorne sandstone is represented by a bed not over 15 feet thick.

In the basin north of Jenny Lind the greatest depth to coal probably does not exceed 800 feet, while in a large part of the district it is within 500 feet of the surface. At Central, a small town about 6 miles northeast of Jenny Lind, coal has been mined from a smaller bed, estimated to lie about 850 feet above the Hartshorne coal, which will be described later in connection with the Charleston horizon. The nature of the coal bed is best shown in this district along the outcrop between Bonanza and Jenny Lind, where it has been mined for about 2½ miles northward from the outcrop. It is thick enough for mining along this crop line for about 10 miles, nearly all the way from Bonanza to Oak Valley post-office, beyond which point it is reported to be too thin for mining and to be divided by partings. In general the bed consists of two benches of coal, with a shale parting near the center. Some of its local variations are shown by the sections presented in fig. 16. At the most eastern point at which the coal has been measured it has a thickness of 2 feet, with a small parting at the center.

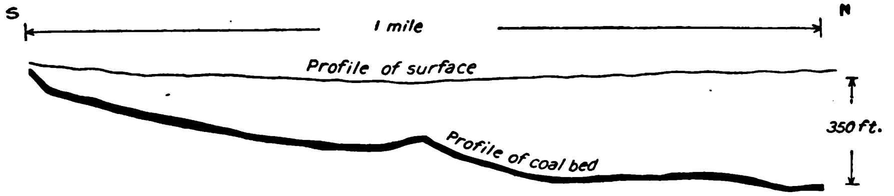


FIG. 15.—Profile of coal bed at Jenny Lind, showing variations in dip.

At Bonanza the Central Coal and Coke Company of Kansas City has two mines, and near Jenny Lind there are two active mines operated by the Western Coal and Mining Company. East of Jenny Lind several strip pits and banks have been mined for local use, the Bostick bank, in sec. 13, T. 8 N., R. 31 W., being the most eastern point.

In the underground workings of the mines there is considerable irregularity in the dip of the coal north of the crop line. In some places along its outcrop the coal dips northward at angles as high as 15°, but after reaching a certain depth the dip flattens rather abruptly, and in some places is locally reversed before it again dips to the north. This condition in mine No. 17 at Jenny Lind is shown graphically in fig. 15.

The relative thickness and the variations of the coal benches and partings in the mines along the outcrop in this district are shown in the sections presented in fig. 16. The coal is thickest in a mine about one-half mile northwest of the town of Jenny Lind. From this mine it gradually thins both eastward and westward, though its thickness varies locally. In these mines the only parting actually rejected in mining is the one that appears in the center of the bed in all the sections measured. This parting varies from less than an inch to over 6 inches in thickness. Although usually shaly, it is variable in character, in some places being described as a soft muck or a hard sulphur band. As a general rule the coal is said to be of better grade where the bed is thin and to contain more impurities in the thicker part. For example, in mine No. 17, at Jenny Lind, where it has the greatest thickness, there is a somewhat irregular band of bony coal, usually not above 1 inch thick, near the center of the upper bench. This is referred to by the miners as the "gray band," but it is not thrown out in mining. In the same mine there is often a sulphur band near the middle of the lower bench. This band is irregular in its occurrence, but is not of sufficient importance to cause any part of the coal to be rejected.

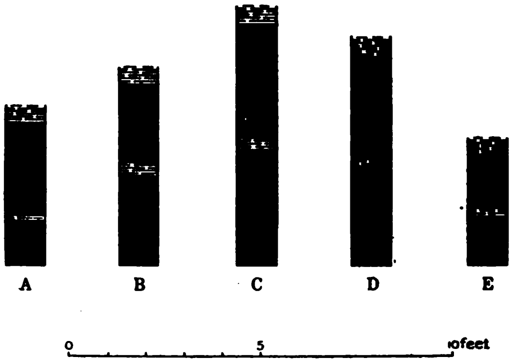


FIG. 16.—Graphic sections of coal along the line of outcrop from Bonanza east to Oak Grove. A, Mine No. 12 at Bonanza, sec. 3, T. 6 N., R. 32 W.; B, mine No. 18, sec. 36, T. 7 N., R. 32 W.; C, mine No. 17, Jenny Lind, sec. 32, T. 7 N., R. 31 W.; D, outcrop on sec. 34, T. 7 N., R. 31 W.; E, Bostick bank, sec. 13, T. 7 N., R. 31 W.

The coal in the upper bench in these mines has a somewhat brighter luster than that in the lower. It is not very distinctly jointed, and although face and butt slips, as they are called, can be found on close inspection, advantage is not taken of them in mining. In some localities a definite system of joints, which do not affect the coal, is apparent in the harder parts of the roof. The roof and floor generally consist of hard, more or less sandy shale; usually the floor is a little harder than the roof. Neither roof nor floor has any features that are especially unfavorable to mining, though in one of the mines, No. 18, near Jenny Lind, parts of the roof are likely to fall out on account of the joints.

The only knowledge we have of the coal beyond the northern limit of present mining development for a distance of several miles is that obtained by drilling. Over a comparatively large area here that is believed to be coal land drill holes have been put down to the coal at rather too long intervals to demonstrate fully the value of the land.

About 6 miles north of the Jenny Lind outcrop, however, this coal bed outcrops again on Massard Prairie, in the center of which there is probably a barren area, surrounded by outcrops of the coal. Coal has been mined from strip pits here for an almost continuous distance of about 3 miles, within which it was possible to measure the coal bed and to study its general appearance and physical character. The variations in the coal bed in its extent northward from the Jenny Lind outcrop to the center of Massard Prairie are shown by the group of graphic sections presented in fig. 17. Throughout this whole distance the bed is characterized by two benches with a varying shale parting between. The coal bed may possibly become progressively thinner northward from the Jenny Lind outcrop, but the field has not been sufficiently tested to demonstrate whether this is true or not. Three of the sections presented in fig. 17 were measured at the outcrop of the coal on Massard Prairie, where it is rather too thin to permit development on a large scale. It is operated, however, in a small way, to supply local demand at Fort Smith. The coal has a luster like that at Jenny Lind. That from the upper bench is brighter but much softer than that of the lower, and is also of a much better quality. The lower bench coal is high in sulphur and ash and after exposure to the air is coated with a white efflorescence. A chemical analysis of coal from Massard Prairie indicates that it may be of a somewhat higher grade chemically than that at Jenny Lind. (See table of analyses, p. 98.)

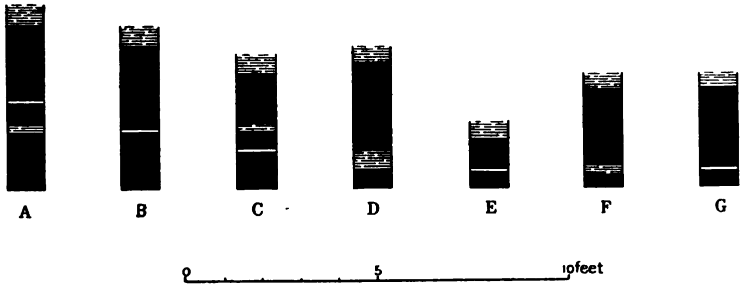


FIG. 17.—Graphic sections of the coal bed from the Jenny Lind outcrop northward to Massard Prairie. A, NW. ¼ sec. 21, T. 7 N., R. 31 W.; B, NE. ¼ sec. 19, T. 7 N., R. 31 W.; C, NE. ¼ sec. 14, T. 7 N., R. 32 W.; D, SE. ¼ sec. 9, T. 7 N., R. 32 W.; E, NE. ¼ sec. 2, T. 7 N., R. 32 W.; F, NE. ¼ sec. 36, T. 8 N., R. 32 W.; G, SW. ¼ sec. 30, T. 8 N., R. 31 W.

From Massard Prairie the coal dips northward at an angle of from 1° to 2° and passes under the town of Fort Smith, where a coal bed approximately 2 feet thick, which is probably identical with this one, has been reported at a depth of 500 feet in a well drilled for gas and oil.

GREENWOOD AND HUNTINGTON DISTRICT.

Location and extent.—The Hartshorne coal bed is continuous over an extensive region south of Backbone Ridge in Sebastian County, where a large number of mines are located along its outcrop. Although the same bed is believed to extend over this whole region, the character of the coal and peculiarities of the bed vary so much locally as to make a number of minor divisions necessary in describing it. In general the whole region could be divided into two parts by a line running south-southwest from Greenwood—a western part in which the coal bed is without partings and free from excessive ash, and an eastern part in which the coal bed is thick but divided and relatively impure. The local character can be more conveniently described, however, under headings which indicate the several centers of mining activity.

Beginning near the Indian Territory line at Hackett the coal outcrop south of Backbone Ridge has been traced eastward for several miles beyond Greenwood, where it turns northward and connects with the outcrop of the coal mined at Bonanza and Jenny Lind. From this line of outcrop the bed dips southward into the Greenwood syncline, south of which it rises and crops out along the flank of a ridge known as Devils Backbone. This ridge, which stretches for miles nearly east and west in an almost straight line and marks the southern boundary of the coal field, turns abruptly southward a few miles southwest of Greenwood and carries the coal outcrop southward to sec. 13, T. 5 N., R. 32 W., which is in the heart of a minor anticline between Midland and Montreal. The outcrop line then turns eastward, the coal dipping southward, and extends in that direction for several miles to Huntington. This town is situated in a syncline, around the end of which the outcrop again turns westward, the coal dipping to the north, and extends in a nearly straight line to Hartford, where it again turns to the east, swinging around the Hartford anticline. The coal bed east of Hartford was followed for only about 10 miles, to a point where the investigation was given up because the bed, although still of considerable size, was found to be so divided by partings as to be of no value. The coal dips to the south from the Hartford anticline and passes under Poteau Mountain, on the south flank of which it again comes to the surface and outcrops for several miles.

Character and thickness of the coal.—From the above description it will be seen that the Greenwood-Huntington district covers a large and roughly rectangular area, including several townships of land on which the almost continuous line of outcrop indicates that the coal bed exists in sufficient size to make it of economic value. In a part of the district, notably that immediately east of the towns of Montreal and Midland, there is an upper coal bed from 40 to 60 feet above the Hartshorne coal, which probably corresponds with the upper Hartshorne coal reported from many points in Indian Territory. Where noted in Arkansas the upper Hartshorne coal is invariably an impure, dirty bed, broken by many shale partings, and is probably nowhere of economic value. The lower coal bed varies in thickness from a minimum of about 2 feet to a maximum of not less than 7 feet. Its floor is usually only a short distance above the hard beds of the Hartshorne sandstone, but its roof is variable. Although it generally consists of shale, a heavy lens of hard, often cross-bedded, sandstone, having a maximum thickness of 60 feet, overlies the coal bed for several miles at Montreal and Burma. In the northwestern part of the district the bed is without partings and is from 2 to 3½ feet thick. In the southeastern part it increases in size, at places, to 6 or 7 feet, and is divided by one or more partings of shale. As a general rule chemical analyses show that the coal is of better quality in the western than in the eastern part of the district.

The coal bed has been opened in a number of mines, small slopes, and strip pits along the whole line of outcrop described, and in some localities the workings have extended back for as much as 1½ miles. Beyond the data obtained by these workings, however, the only information as to the character of the coal is that derived from a few scattering drill holes. While it can not be said that the whole district has been prospected sufficiently to prove that it is all underlain by valuable deposits of coal, the evidence at hand seems to indicate that the greater part is valuable coal land. The maximum depths of the coal below the surface will be found beneath Sugarloaf and Poteau mountains, where the depth is from 1,400 to 2,500 feet. On the lower lands surrounding Sugarloaf Mountain the coal probably does not lie at a greater depth than 900 feet at any point, while its average depth probably does not exceed 600 feet, as indicated by the distribution of formations shown on the geologic map (Pl. VI). The various mines and openings at which the coal has been examined may be best described in order following the lines of outcrop.

Hackett region.—On the outcrop lines south of Backbone Ridge coal has been mined at many small openings between Hackett and Greenwood and from several larger mines east of Greenwood. The Midland Valley Railroad was located and built as near as possible to this line of outcrop in order to facilitate the marketing of the coal. The thickness of bed, partings, and benches, together with their variations, are shown in the series of graphic sections, fig. 18, from which it will be seen that the coal bed at the State line consists of one bench of good coal without partings, having a thickness of 3½ feet. This general condition of the bed holds to within a mile of the town of Greenwood, east of which the bed thickens rapidly and is divided into two or more benches by shale partings.

Samples and analyses of the coal mined in the vicinity of Hackett and Excelsior indicate that for about 8 miles along this outcrop line the coal is unusually free from ash and other impurities and that its efficiency must be comparatively very high. In this respect it resembles the coals mined near Montreal and Midland, described later. From Hackett to Excelsior the bed is without partings, and varies in thickness from 2 to 3½ feet.

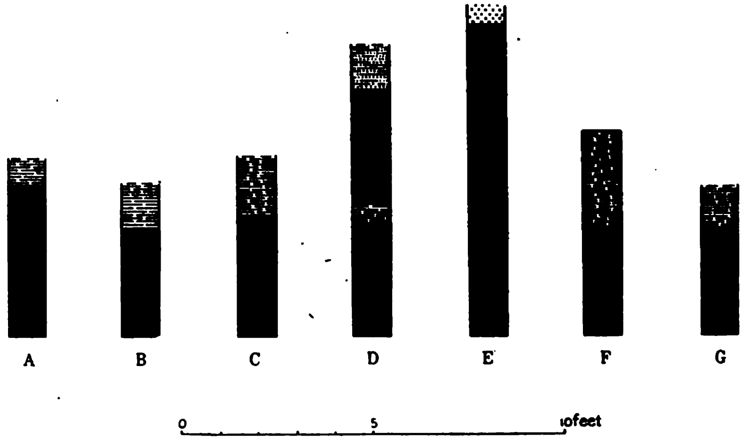


FIG. 18.—Graphic sections of coal showing variations along outcrop from Hackett east through Greenwood and Fidelity. A, Hackett City Smokeless Coal Company mine, sec. 21, T. 6 N., R. 32 W.; B, Bates and McWilliams mine, sec. 23, T. 6 N., R. 31 W.; C, Skinner mine, sec. 17, T. 6 N., R. 31 W.; D, Greenwood Coal and Lumber Company mine, sec. 12, T. 6 N., R. 31 W.; E, Banner mine, Fidelity Coal Company, sec. 6, T. 6 N., R. 30 W.; F, section at old McConnell pit, sec. 32, T. 7 N., R. 30 W., as given in Ann. Rept. Geol. Survey Arkansas, 1888, vol. 3, p. 16; G, drill hole, sec. 14, T. 7 N., R. 30 W.

The floor is a sandy shale with a hard sandstone a short distance below. The roof generally is a hard shale, which stands well, but in some of the mines there is a varying amount of draw slate above the coal.

Although indistinct joints that form face and butt slips in the coal can be recognized in nearly every mine, advantage is not taken of them in mining. The coal generally has a bright, live luster and a somewhat granular fracture. Coal was at one time extensively mined near the town of Hackett by the Central Coal and Coke Company, but the works there are said to have been abandoned on account of bad roof. The Smokeless Coal Company, of Hackett, recently opened a new mine about half a mile west of the town, and though it is reported that 6 or 8 inches of draw slate occurs above the bed no difficulty is experienced with the roof. There are also two or three small mines in operation near Excelsior, and several old slopes and strip pits at other points. Many of these mines are small and are worked by undercutting with the pick.

Greenwood region.—In several mines east of Greenwood the character of the coal bed differs from that seen in mines near Hackett, the bed being very much thicker but divided by shale partings, as shown in fig. 18. Analyses of the coal show a much higher percentage of ash than that contained in the coal of the smaller bed at Hackett. In the mine of the Greenwood Coal and Lumber Company, in sec. 12, T. 6 N., R. 31 W., the coal has a maximum thickness of 7 feet, with a parting of shale near the center which varies in thickness from a fraction of an inch to 6 inches. Two miles farther east, at the Fidelity Fuel Company's mine, the bed is nearly 6 feet thick with a large shale parting in the upper half.

East of the mine of the Fidelity Fuel Company no operations are now in progress on this bed. It was formerly worked about 1 mile farther east, at an opening known as McConnell's, which is at present abandoned. The section measured here by the geologists of the Arkansas Survey gives only 33 inches of coal, with a shale parting near the top. Beyond this no measurements have been made on the outcrop of the coal, though it has been occasionally seen in wells and other accidental exposures. Near Auburn it is reported to have a thickness of 18 inches. A diamond-drill hole in sec. 14, T. 7 N., R. 30 W., 3 miles north of Auburn, showed that this coal bed was there 33 inches thick, 9 inches of which was reported as bone. East of this point the coal is not exposed for many miles, and no measurements have been made.

In all of the mines and openings noted the floor of the coal is only a few inches above a bed of hard sandstone, the upper member of the Hartshorne formation. The roof is invariably sandy shale.

On the outcrop line which follows Devils Backbone Ridge, southeast of Greenwood, small exposures have been found at points several miles east of Greenwood, the positions of which are shown on the geologic map. No coal has been produced at any of these points, nor have the coal beds been opened sufficiently to permit accurate measurements. The inclosing rocks here are tilted at a high angle, in some places are slightly overturned and probably sheared, so that the coal bed is probably more or less crushed. Small amounts of coal have been obtained from a strip pit in sec. 18, T. 6 N., R. 30 W., at a point where Vache Grasse Creek cuts across Backbone Ridge, but the workings have all been abandoned, and it was impossible to learn the exact thickness of the coal or the detail of its section.

Montreal, Burma, and Midland regions.—Along the outcrop line running southwest from Greenwood to Montreal and Midland the coal bed, as far as known, is without partings, and the quality of the coal resembles that at Hackett. Most of the development is to be found near Midland, about 10 miles southwest of Greenwood, though the general character of the bed and quality of the coal through a large area seem to be practically uniform, as shown by the graphic sections presented in fig. 19 and by the table of analyses.

About 2 miles southwest of the town of Greenwood coal has been mined recently from a small slope on sec. 21, T. 6 N., R. 31 W. At this point the coal dips northward at an angle of about 15° and has a thickness of 24 to 30 inches, without partings. The same bed of coal is opened again at the Moran mine, a slope on sec. 8, T. 5 N., R. 31 W., where it has a thickness of 40 inches without partings. South of this point there are many openings, both new and old, and it is usually not difficult to trace the line of outcrop, although it is obscured by an overlying lens of sandstone that resembles in all respects the Hartshorne sandstone and has a maximum thickness of 60 feet. In general the exposures show from 2 to 4 feet of coal without partings. The coal bed dips at angles varying from 1° to 15°, but it seems to be invariably true that where the dip is high at the outcrop it rapidly decreases and the coal bed flattens out in depth.

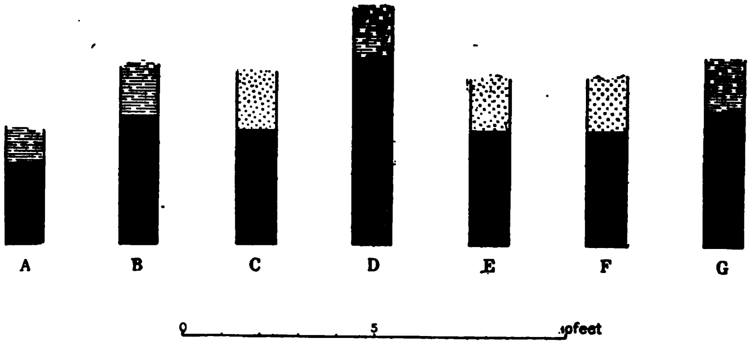


FIG. 19.—Graphic sections showing variations of coal bed and roof along outcrop in Montreal, Burma, and Midland regions. A, Slope on sec. 21, T. 6 N., R. 31 W.; B, Moran mine, sec. 8, T. 5 N., R. 31 W.; C, Irby mine, sec 7., T. 5 N., R. 31 W.; D, Banner Coal Company, sec. 19, T. 5 N., R. 31 W.; E, Denman Coal Company, sec. 19, T. 5 N., R. 31 W.; F, Turnipseed mine, sec. 20, T. 5 N., R. 31 W.; G, strip pit on sec. 21, T. 5 N., R. 31 W.

A rather unexpected variation, locally described as a fault, occurs near the center of sec. 20, T. 5 N., R. 31 W., in the entry to a small slope mine where the coal, which in the mine has a thickness of over 3 feet, very suddenly changes in character and beds of shale abruptly take its place, the shale fingering in with lenses of coal. East of this place for a distance of about 1 mile the bed, as exposed by prospecting along the outcrop, consists for the most part of shale and bone, but contains very little good coal. The coal is of good quality again in a strip pit near the south line of sec. 21, T. 5 N., R. 31 W., from which point it has been traced eastward to Huntington. In this distance the bed changes rapidly, becoming very much thicker and being divided by several partings.

In the vicinity of Midland and Burma an upper bed of coal, corresponding to the upper Hartshorne coal of Indian Territory, is indicated by drill records. This bed averages 60 feet above the lower one. It has a maximum thickness of approximately 5 feet, but is generally shaly or bony, and is described as a "dirty vein." It is not mined anywhere in Arkansas, though it may be found to be of some importance toward the Indian Territory line.

Huntington region.—The coal bed in the Huntington basin resembles that at Greenwood. Although characterized by great thickness it is divided by shale partings, and chemical analyses of the merchantable coal show that it contains a rather high percentage of ash. This character of the bed continues southwest along the outcrop nearly to Hartford, where the bed is not divided. East of Hartford, on the outcrop that lies south of the Hartford anticline, the bed becomes so much divided by partings as to be of little value.

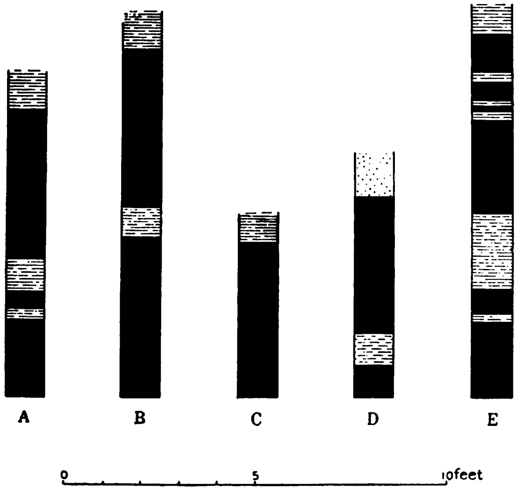


FIG. 20.—Graphic sections of coal bed along outcrop from Huntington through Hartford to the Chasteen slope. A, Mine No. 2, Central Coal and Coke Co., sec. 26, T. 5 N., R. 31 W.; B, Mammoth vein mine, sec. 1, T. 4 N., R. 32 E.; C, Bolen and Darnall mine, sec. 10, T. 5 N., R. 32 E.; D, Patterson Coal Company mine No. 1, sec. 14, T. 4 N., R. 32 W.; E, Chasteen pit, sec. 18, T. 4 N., R. 31 W.

The variations in the bed along the outcrop from Huntington to Hartford and then eastward along the southern outcrop are shown graphically in fig. 20. From the center of sec. 22, T. 5 N., R. 31 W., the coal has been stripped almost continuously along the outcrop for 2½ miles to the town of Huntington, where the outcrop and accompanying strip pit swing around a half circle to the south and then extend southeastward toward Hartford. There are two large mines operated from shafts as well as these strip pits in the synclinal basin near Huntington. The coal is in three benches separated by thin shale partings.

For several miles southeast of Huntington the coal is not mined, though the position of the outcrop has been determined by prospecting. It is mined again, however, in sec. 32, T. 5 N., R. 31 W., where the bed known as the Mammoth vein is over 8 feet thick, including a parting of several inches of shale near its center. At the town of Hartford, in sec. 10, T. 4 N., R. 32 W., the coal is worked in a number of small slopes and in two large ones. It consists here of a single bench of coal about 3½ feet thick. From this point the coal outcrop swings eastward around the western end of the Hartford anticline, and the coal is again mined in secs. 13 and 14, T. 4 N., R. 32 W. The coal bed here resembles the Huntington coal in that it consists of several benches of coal with partings between. East of this point there are no active mines. Although the coal has been prospected here, it is common report that the bed is separated into many benches. At the Chasteen mine, in sec. 18, T. 4 N., R. 31 W., it is very much divided and contains no bench over 2½ feet thick, though the total thickness of the bed is near 8 feet. East of this point no measurements have been made, though the outcrop of the coal has been traced for a number of miles.

Depths to the coal.—The coal dips westward at a low angle from the line of outcrop from Greenwood to Burma, but probably does not reach a depth of more than 800 feet below the surface at any point. The synclinal trough in which the town of Huntington is situated extends westward to the State line and includes Sugarloaf Mountains. For several miles west from Huntington the coal lies within 400 feet of the surface. It reaches its greatest depth in Sugarloaf Mountains, where it can probably all be reached by tunnels or slopes and should not be regarded as inaccessible. The anticline on which the town of Hartford is situated also extends southwestward to the Arkansas-Indian Territory boundary and along it the coal is all near the surface. Drill holes which have been sunk near the boundary line indicate that the greatest depth on this anticline at the boundary will not exceed 800 feet. South of the Hartford anticline the coal dips at a rather high angle and passes under Poteau Mountain. Some of the coal here is probably scarcely fit for mining on account of the divided condition of the coal bed, but further prospecting will no doubt develop a large area of coal land worthy of attention in this region also. The variations in the quality of the coal from the different mines of this district is indicated by the analyses in the table on pages 96–97.

BATES AND COALDALE DISTRICT.

The coal bed which dips southward from Hartford and passes under Poteau and Whiteoak mountains comes to the surface again in a line of outcrop parallel with the south flank of Poteau Mountain, where it has been traced from the Indian Territory line eastward for a distance of about 20 miles. It is continuous with the outcrop of coal beds mined in Indian Territory. Two analyses from samples taken at the Seymour mine near Bates indicate that the coal is distinctly bituminous in character and lower in the scale of classification than the other coals of the Arkansas field. The workings at Coaldale near the State line were not examined, but section A of the bed given in fig. 21 was reported by the operator. The bed here consists of over 7 feet of coal divided by a parting of shale. Three miles east of the State line, in sec. 21, T. 3 N., R. 32 W., the coal bed is divided into three benches and contains an aggregate of 8 feet of coal. Mining is done only in the largest bench, which is 4 feet thick. Nine miles farther east the coal bed still has a thickness of 5 or 6 feet, but is divided into many small benches, the largest of which is only 12 inches thick, and it is not probable that the coal can be successfully mined in this locality, though it is possible that the lower part of the bed was not all exposed. Croppings of this bed have been observed for about 2 miles farther east, but it has nowhere been opened so that a section could be measured, nor have any reports indicating a workable coal bed been received. These variations are shown by the graphic sections presented in fig. 21. The portion of the coal field that extends eastward from Lookout Gap and underlies Whiteoak Mountain was not examined, owing to the short time available for field work. Although the Hartshorne horizon is known to extend over a considerable area here, the facts presented indicate that the coal bed is probably divided and of little value. Both north and south of Poteau Mountain the coal dips at a high angle and the rocks maintain this dip well toward the center of the basin, indicating that the coal there is very deep. It is probable, however, that all of the coal can be mined from slopes entering the basin from the north and south sides.

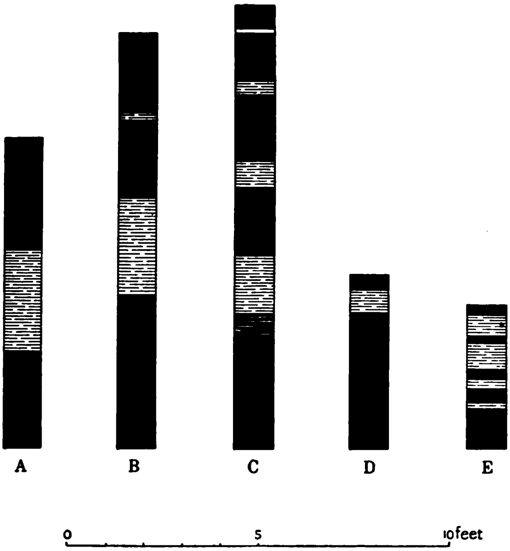


FIG. 21.—Characteristic sections of coal bed on outcrop south of Poteau Mountain. A, Witte Coal Company mine, sec. 19, T. 3 N., R. 32 W.; B, Seymour mine, sec. 21, T. 3 N., R. 32 W.; C, prospect hole in sec. 21, T. 3 N., R. 32 W.; D, Davidson slope, sec. 16, T. 3 N., R. 32 W., upper part of bed probably omitted; E, prospect hole in sec. 1, T. 3 N., R. 31 W.

CHARLESTON AND PARIS DISTRICT.

The Hartshorne coal has not been opened nor has the thickness of the bed been measured on the outcrop east of Auburn for a distance of about 35 miles, to what will be described as the Prairie View district. This unexplored region includes the towns of Charleston and Paris, near *which coals* of higher horizons are mined. The horizon of the Hartshorne coal outcrops through the whole length of this region along the north base of Devils Backbone Ridge and its eastern extension, Pine Ridge. It also outcrops near the southern base of Mill Creek Ridge, on Grand Prairie, which extends from the Arkansas River at the mouth of Vache Grasse Creek eastward to Roseville. Along the southern outcrop line the presence of the bed is occasionally indicated by coal smut, but it is nowhere so exposed that its thickness can be measured, and the natural conclusion to be drawn is that along this line the bed is thin and of no economic value.

Along the northern outcrop, on Grand Prairie, no exposures of coal were seen by members of our party. There are some indications of a fault along the north side of this prairie, and it is possible that the coal horizon does not reach the surface, though it can not be at a very great depth. In the preliminary report of the Arkansas State Survey it is noted that coal occurs near the town of Vesta, probably at the Hartshorne horizon. This coal has been found in several wells near that place, but present information regarding it is no more advanced than that given by the State Survey. So far as known this coal bed has never been opened or accurately measured. Coal has been reported in a few shallow wells that penetrate the sandstone mantling Mill Creek Ridge near the town of Sub Rosa. If these reports are true this may possibly be the Hartshorne bed, though the stratigraphic evidence seems to locate it in the Hartshorne sandstone at a short distance below the general coal horizon.

The Hartshorne coal has been penetrated by diamond drills 3 miles northwest of Charleston, where it is approximately 2 feet thick and has a shale parting. East of this point the coal bed would be found at a depth usually exceeding 400 feet. At the base of Potato Hill and also at Paris its depth is estimated to be approximately 1,000 feet, while at Charleston it can probably be reached at from 800 to 900 feet. Between the towns of Branch and Caulksville there is an anticlinal flexure which probably brings the Hartshorne coal horizon within 300 or 400 feet of the surface. Although a certain amount of drilling has been done near Charleston and also near Paris, it is probable that none of the wells have reached a sufficient depth to find the Hartshorne coal.

South of Prairie View the Hartshorne sandstone is brought to the surface in an anticlinal flexure, along the axis of which there is a profound fault, as has been shown. A coal bed, presumably the Hartshorne, outcrops north of this anticline, and its extent has been partly determined by a number of drill holes, though the western boundary of the workable coal area can not be regarded as determined. South of the Prairie View anticline the Hartshorne horizon is present in a narrow syncline between it and Pine Ridge. No outcrop of the coal has been discovered here, though the bed has been penetrated by drill holes which indicate a thickness less than 18 inches. A coal bed about 400 feet below the Hartshorne sandstone outcrops at a number of places south of Pine Ridge and has in some localities been mistaken for the Hartshorne coal. It has been worked in strip pits in sec. 20, T. 7 N., R. 24 W., south of Ellsworth, but prospecting has not shown that the coal is of commercial value.

Coal of the Hartshorne horizon is also mined in the Denning and Coal Hill district, from which the coal bed dips southward at a rather low angle toward the Paris syncline. Drill records here indicate that the coal bed thins rapidly south of Denning, although its southern limit was not reached.

From the above facts it will be seen that the Hartshorne coal underlies a large area, about 15 miles wide, extending from Auburn eastward to Prairie View, in which the thickness and value of the coal has not been determined. The outcrops along the north and south sides of this area reveal no coal of commercial importance, but in view of the great local variation that may be expected in the Hartshorne coal further prospecting by deep drilling is fully warranted. The coal horizon can certainly be reached by a series of drill holes less than 400 feet deep on Grand Prairie along the northern edge of the basin and also in the center of the Caulksville anticline. The beds are so highly tilted and the structure so broken along the southern edge of the basin that the coal there would probably be of little value if found.

VAN BUREN AND ALMA DISTRICT.

Much that has been said in regard to the Charleston and Paris district can well be repeated in regard to the region north of the river in the vicinity of Van Buren and Alma. It is a district that has not been thoroughly prospected, though stratigraphic investigations show that it is underlain by the Hartshorne coal.

The coal outcrops at several places in the vicinity of Mulberry, where there is a small coal bed at a horizon very close to if not identical with that of the Hartshorne coal, which is usually overlain by 20 or 30 feet of sandstone and sandy shale that lies near the base of the Spadra formation. West of Mulberry the coal horizon is at a greater depth and does not outcrop, since at the northern edge of the field it is cut off by a fault north of which the Winslow sandstone is exposed. The depth of the Hartshorne horizon could not be estimated closely on account of the very obscure stratigraphic evidence, much of the surface being covered with deposits of gravel and sand.

A small coal bed found near Alma and Van Buren is provisionally correlated with the Charleston coal, which is about 800 feet above the Hartshorne horizon. What is probably the Hartshorne bed has been reached in a drill hole near Alma at a depth of 700 feet. It is reported to be 9 inches thick and overlies a sandstone 150 feet thick, provisionally correlated with the Hartshorne. A small coal bed which may also correspond with the Hartshorne coal was formerly mined at the Hendricks pit, in sec. 16, T. 9 N., R. 31 W., 2 miles northeast of Van Buren.[a] This coal bed is said to be 2 feet thick. It overlies a hard, massive sandstone which is possibly equivalent to the Hartshorne. A coal bed is also reported in a number of wells in Van Buren which can not be definitely correlated with that south of the river from the stratigraphic evidence available, but probably corresponds very nearly with the Charleston coal. If this interpretation of the stratigraphy is correct, it necessitates the presence of a fault with a displacement of about 800 feet between the coal 2 miles northeast of Van Buren and that just mentioned. None of these coal beds have been found to be of sufficient size to warrant systematic development.

COAL HILL AND DENNING DISTRICT.

The Coal Hill and Denning district lies north of the Arkansas, between the river and the main line of the Iron Mountain Railway, about 40 miles east of the Indian Territory line. Its general outline and structure are shown in fig. 22. Along its north side the coal is cut off by a fault extending from Denning to a point a few miles east of Coal Hill, north of which the underlying rocks are raised. Half a mile south of this fault there is an anticlinal axis extending east and west through the district, in the center of which the underlying barren rocks are exposed south of Coal Hill. Near Denning the anticline pitches below the surface and the coal bed is continuous across it. South of Altus, at the west end of the Coal Hill fault, the coal bed approaches the surface, as indicated by drill records, and the Hartshorne sandstone rises and mantles Altus Hill.

A few miles west of Altus there is a smaller basin of coal land, including possibly 1 square mile, resting on this sandstone. The southern limb of the Coal Hill anticline, about 2 miles south of Coal Hill, is thrown down by the Spadra fault, so that the coal does not reach the surface.

Coal has been mined almost continuously from Coal Hill to Denning and southeastward from Denning around the southern limb of the anticline for several miles. The coal ranges in thickness from 1 to 5 feet, and the bed is usually characterized by a parting of shale or clay near the center, which varies greatly within short distances, being so thick in a number of places as to render the bed of no value.

Generally the parting thickens along the northern edge of the field, so that the underground workings have been stopped before they reach the fault. One of the first shafts sunk here for mining purposes found the parting over 4 feet in thickness and was abandoned for mining purposes, though it is still used as a pump shaft to drain one of the mines farther south. South of the anticline coal has been mined near the outcrop, but beyond half a mile from the outcrop it is known only by rather meager drill records. These indicate that the bed becomes thin and of little value before the river is reached. Very little prospecting for this coal has been done at any distance south of the Coal Hill anticline, though its presence at a considerable depth has been demonstrated by drilling, and it is reported that the parting is so thick as to preclude the possibility of successful mining. This coal bed probably extends eastward south of Hartman and is identical with that mined at Spadra, but for several miles the prospecting has not been sufficient to determine its quality and it does not outcrop at the surface. It will be found at a depth of several hundred feet and will doubtless present a number of difficulties for mining,

---

[a] Ann. Rept. Geol. Survey Arkansas, 1888, vol. 3, p. 21.

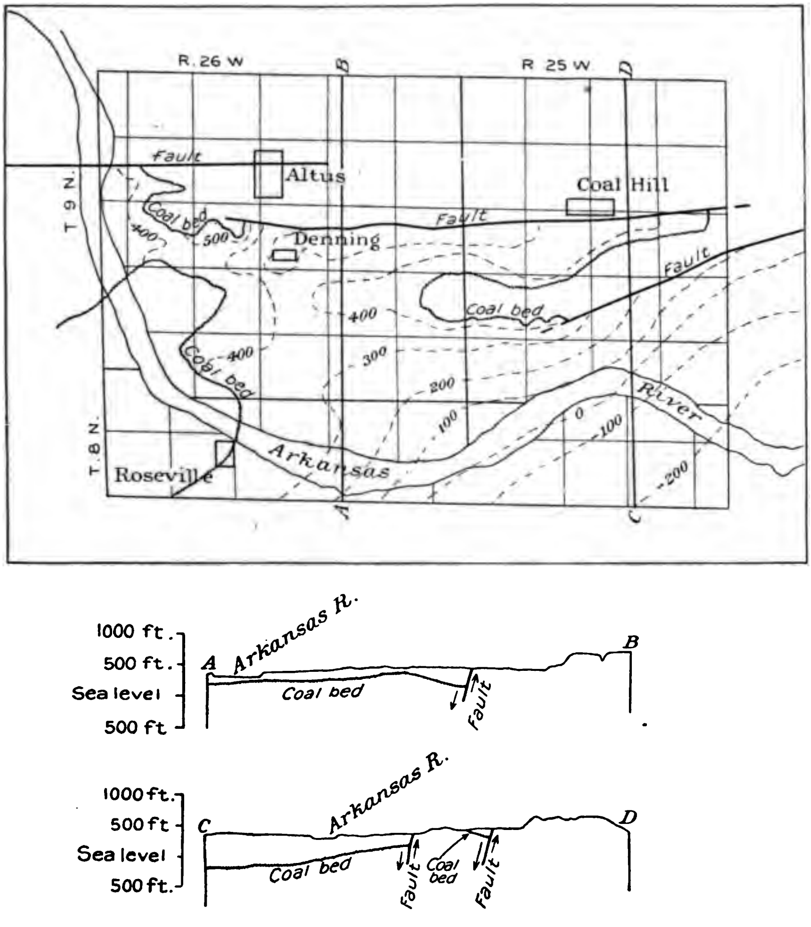


FIG. 22.—Map showing structure of Coal Hill-Denning district. Underground contour interval 100 feet. Diagrammatic profiles of land surface and coal bed along lines *A-B* and *C-D*; horizontal scale, 1 inch=3 miles; vertical scale, 1 inch=3,000 feet.

since it is below the flood plain of Arkansas River and the hard rocks are overlain by thick alluvial deposits.

Variations in the thickness of the coal and its partings in the Coal Hill district are shown graphically in fig. 23. The coal is semi-bituminous, as is shown by chemical analyses. It has a bright luster and is somewhat harder than that mined at the west end of the field.

Coal is mined for local trade from a number of small slopes in the small outlying basin west of Altus, in sec. 17, T. 9 N., R. 26 W. Here there are two coal beds, the lower averaging 2 feet and the upper 10 inches thick, with 18 feet of sandy shale between them. These two beds are regarded as equivalent to the two benches of the Denning coal bed with an excessive thickness for the parting. The coal resembles that of the Denning bed, though, being shallow, it is affected by weathering and the joints are iron stained. Chemically it has a much lower percentage of sulphur.

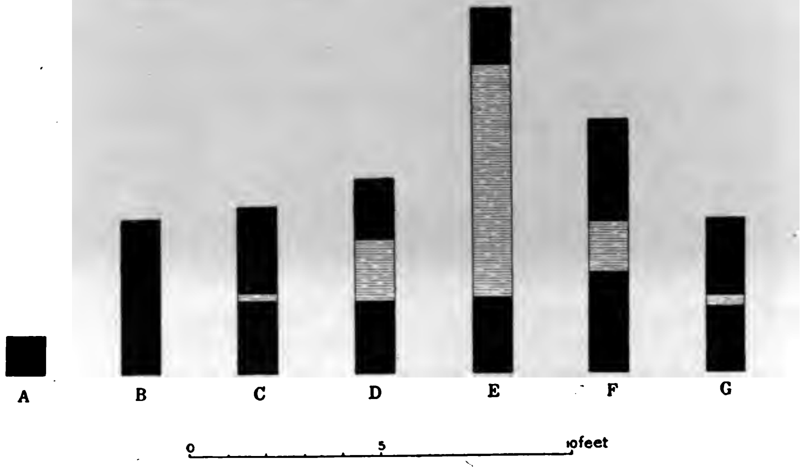


FIG. 23.—Graphic sections of coal at Denning, showing variations of the parting as revealed by drill records and other openings. A, Drill hole in NW. ¼ sec. 34, T. 9 N., R. 26 W.; B, drill hole in SW. ¼ sec. 27, T. 9 N., R. 26 W.; C, drill hole in NW. ¼ sec. 27 (average section of the bed as reported by Western Coal and Mining Co.); D, drill hole in NW. ¼ sec. 26, T. 9 N., R. 26 W.; E, drill hole near pump shaft in SW. ¼ sec. 23, T. 9 N., R. 26 W.; F, drill hole in SE. ¼ sec. 23, T. 9 N., R. 26 W.; G, drill hole near old Stiewell slope, sec. 20, T. 9 N., R. 25 W.

A similar coal bed, with a parting more than 12 feet thick, is indicated by outcrops of coal smut on the south side of the river about 2 miles west of this basin in sec. 23 of the same township. No coal has been mined here. The outcrop probably indicates a small shallow basin of coal of the Hartshorne horizon resting on the Hartshorne sandstone.

SPADRA DISTRICT.

This district is also north of Arkansas River and its center is about 10 miles east of Coal Hill. It takes its name from the town of Spadra, near which the coal bed outcrops and where the first developments were made. The coal differs slightly from that at Denning, in that it is considerably harder and of higher grade chemically. It is mined almost exclusively for domestic use and sold as semianthracite or Arkansas anthracite coal. The coal is somewhat thinner than at Coal Hill and Denning, though it is regarded as a continuation of the same bed, and it presents similar irregularities.

The structure of the Spadra field (fig. 24) is complicated, and its interpretation is made difficult by extensive deposits of sand and gravel, which conceal a large part of the surface. It has been prospected by many companies and individuals, and though numerous drill holes have penetrated the coal horizon it has been impossible to assemble all of the information that has been obtained, since some of the records have been lost and others probably withheld. The available information, however, is sufficient to show that the continuity of the coal bed is broken by several faults of normal type that strike approximately east and west with downthrows generally to the south. Only one of these has been encountered in the mine workings, and its

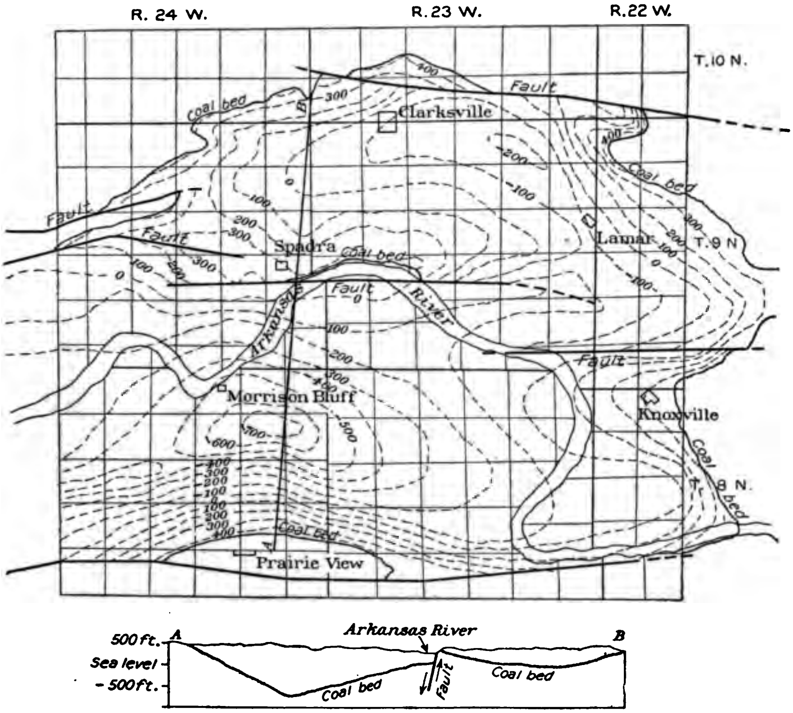


FIG. 24.—Map of Spadra and Prairie View coal fields, showing the nature of the deformation and faulting of the coal bed. Underground contour interval, 100 feet. Profiles of land surface and coal bed along line *A-B*. Vertical scale, 1 inch=4,000 feet. Horizontal scale, 1 inch=4 miles. Elevation of river at average stages, 300 to 320 feet.

extension conclusively demonstrated by drill holes. The others are indicated by stratigraphic evidence. The best known of these faults was first encountered 2 miles northwest of Spadra in one of the mines of the Eureka Coal Company, from which point it extends west-northwest nearly to the town of Hartman, where it turns a little south of west and continues to the center of the Coal Hill field.

Another fault, trending nearly east and west, marks approximately the southern limit of present mining operations. It is parallel with and a short distance north of Spadra Hill, a long ridge capped by flat-lying sandstone south of Spadra, and its east end is a few hundred yards north of the branch railroad at the south base of Big Danger Hill, in sec. 23, T. 9 N., R. 23 W., where its position is indicated by conclusive stratigraphic evidence. The displacement at the mouth of Spadra Creek is at least 200 feet. A small fault, which differs from those described in that the downthrow is to the north, lies north of the western part of the Spadra field, bringing in a small area of Spadra coal at the old Allen slope in sec. 18, T. 9 N., R. 24 W.

Another fault, which marks the northern boundary of the coal field northwest of Clarksville, occurs 3 miles north of Cabin Creek. The west end of this fault is probably north of Clarksville, from which point it extends eastward for about 15 miles. North of this fault the barren rocks below the coal horizon are exposed.

From Spadra the coal bed extends northward for about 5 miles. It underlies the town of Clarksville at a depth of from 400 to 500 feet, and outcrops 1½ miles northwest of Clarksville at a point noted by the Geological Survey of Arkansas as the Harkreader well,[a] from which point the outcrop can not be traced eastward with certainty. Coal again occurs and has been mined at a point 2 miles northeast of Clarksville, in what is known as the Mason drift, sec. 27, T. 10 N., R. 23 W. While it is probable that this coal is in the Hartshorne horizon, its characteristics are quite different from those of the Spadra bed, as will be shown later. The Spadra bed is known to extend from Spadra and Clarksville eastward, where it underlies Big Danger Hill and the massive sandstone of which it is composed. It has been penetrated by drill holes west of Cabin Creek (Lamar) at a depth of 550 feet, and the same bed probably outcrops on sections 6 and 7, T. 9 N., R. 23 W., 2 miles north of Cabin Creek.

The rather complicated structure of the coal field, as interpreted, is presented in the sketch map forming fig. 24, from which it will be seen that at the western limit of prospecting the coal bed is at a depth of 400 feet and that its depth probably increases westward.

On account of the miners' strike it was impossible to obtain measurements of the coal at the extreme west end of the district, though the coal bed had been reached in one of the shafts. A number of drill holes have been made in this part of the field, but the owners would furnish no information regarding the coal except its distance below the surface. The coal bed is exposed by outcrop at the old Allen slope, in sec. 18, T. 9 N., R. 24 W., and also in an unnamed slope on section 17 of the same township, both of which have been abandoned for many years. The Allen slope, however, was open at the time the field was examined by the geologists of the Arkansas Survey, who report that the coal bed measures 4 feet, including a thin parting near the center. Old residents say that the coal is 3 feet thick at the slope in section 17, and the impression gained by conversation with mine owners and operators interested in the western part of the Spadra field is that approximately this thickness prevails over the entire west end of the field.

---

[a] Ann. Rept. Geol. Survey Arkansas, 1888, vol. 3, p. 24.

Coal mines are located at very short intervals from a point a short distance west of Montana post-office eastward along the railroad for a distance of 6 or 7 miles. Nearly all of the openings are made by shafts that reach the coal at a depth of 200 feet or less. The average thickness of the coal is 2½ feet, including a small parting near the center of the bed. In general the coal dips to the north or northwest at a low angle, usually less than 3 per cent. The variations in the thickness of the coal bed and the position and size of the parting are shown in fig. 25.

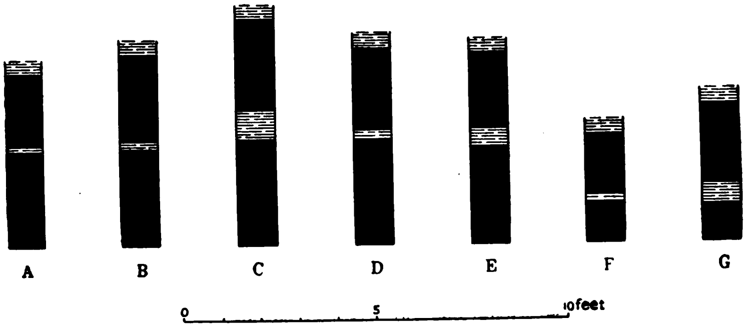


FIG. 25.—Sections showing thickness of the coal bed in the Spadra district and in the undeveloped field north of Lamar. A, Scranton Anthracite Co. mine, sec. 22, T. 9 N., R. 24 W.; B, Central Anthracite Co., sec. 22, T. 9 N., R. 24 W.; C, Eureka Anthracite Co., sec. 23, T. 9 N., R. 24 W.; D, Spadra Creek Coal Co., Needmore mine, sec. 23, T. 9 N., R. 24 W.; E, Consolidated Anthracite Coal Co., mine No. 1, sec. 24, T. 9 N., R. 23 W.; F, Brooks mine, Western Anthracite Coal Co., sec. 17, T. 9 N., R. 23 W.; G, prospect on sec. 7, T. 9 N., R. 22 W., north of Lamar.

The underground workings of the mines near Spadra extend for a maximum distance of 1 mile north from the main line of the Iron Mountain Railway, and two new mines have recently been opened near the southwest face of Big Danger Hill, about 2 miles northeast of Spadra. Although the records of much of the drilling that has been done north of these mines were not available, it is common report that in that direction the parting increases rapidly and makes much of the coal unfit for mining. A shaft about 1½ miles northwest of Clarksville, near the old Harkreader well, was sunk in 1906, but had not reached the coal at the time of our examination. The coal bed, however, outcrops a short distance to the southwest, where it shows a thickness of 18 to 24 inches without parting.

At all of the mines and openings described thus far the coal bed is overlain directly by shale. The coal bed at the old Mason slope, which has been correlated provisionally with the Spadra coal, is different, however, in that it is overlain by several feet of hard sandstone. Coal has been mined from a strip pit 1½ miles southeast of the Mason drift, probably from a somewhat higher bed, though the exact location of the old pit is obliterated, and it was impossible to determine its stratigraphic position. In view of the tendency of the coal bed at Denning to divide in areas farther north, it seems at least possible that the same tendency may appear in the Spadra field—that the parting increases rapidly northward, separating the Spadra coal into two beds. The Mason coal may therefore represent the lower bench of the Spadra bed. The coal at the Mason slope is protected from erosion by the thin bed of sandstone which overlies it, and remnants of the coal bed have been found mantling the hill to the north at a number of places. Presumably it is the same bed that outcrops in a thickness of 15 inches on Dicks Branch, in sec. 10, T. 10 N., R. 23 W., 2 miles north of the Mason opening. It has been noted that the Spadra coal is believed to outcrop again northeast of Cabin Creek, where it has been opened at two points and seems to be sufficiently thick to warrant development. The section measured there is over 2 feet thick and is shown in fig. 25. From these openings the coal bed has been traced eastward and is correlated with two outcrops which are shown on the map near Piney Creek. At this point, however, the coal is of no value. It consists of 7 inches of coal overlying 2 feet of bony coal.

PRAIRIE VIEW DISTRICT.

This coal field lies on the south side of Arkansas River immediately south of the Spadra district. The presence of coal near the village of Prairie View has been known for many years and was noted in the report of the State Survey.[a] Attempts to prospect the field and determine the extent of the coal land have been made only within the last few years, and large areas of land have been purchased or optioned by a company known as the Arkansas Anthracite Company, whose headquarters are at Little Rock.

In the examination of the field preparatory to the purchase of coal lands 37 drill holes were sunk to various depths, 13 of which reached the Hartshorne horizon and found workable coal. A number of the holes were evidently not carried to depths sufficient to reach the horizon sought, while others showed that there are parts of the field in which the coal is too thin for exploitation. The greatest thickness of the Hartshorne coal reported is 5 feet and the least about 1 foot.

---

[a] Ann. Rept. Geol. Survey Arkansas, 1888, vol. 3, p. 25.

This field lies in a broad syncline having a general east-west axis. Its southern edge is along the Prairie View fault, and its northern edge, which is contiguous to the southern edge of the Spadra field, is along the Big Danger fault, both of which have been described. A large part of the land surface is covered with heavy deposits of sand and gravel, so that inferences drawn from bed-rock exposures are not of very great value. The structure of the field, as indicated by drill records and observations of outcrops, is shown in fig. 24.

Three analyses of coal from diamond-drill cores, obtained at different points in the field, published in the prospectus of the Arkansas Anthracite Company, are given in the table on page 88. The samples appear to be fully representative of the beds, and the analyses, which seem to be reliable, indicate that the coal in the northern part of the field is semianthracite, like that of the Spadra district, while that of the southern part is semibituminous, like that at Coal Hill. This is a condition to be expected from the facts learned in other parts of the Arkansas field. In the northern part of this district the bed is divided into two benches, resembling in this respect the Spadra coal, but in the southern half no parting is reported. Several graphic sections of the bed, as reported by engineers of the coal company, are given in fig. 26.

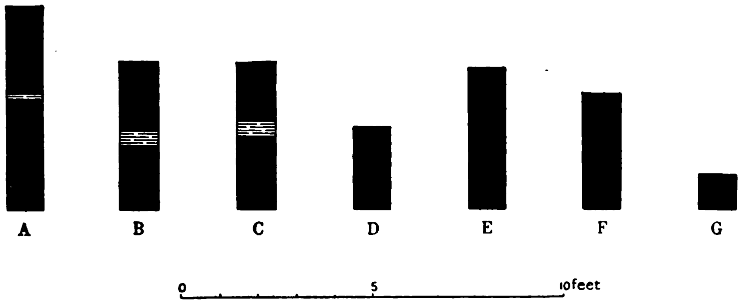


FIG. 26.—Graphic sections showing approximate thickness of coal at various points in the Prairie View field. A, B, and C from northern part of field; D, E, F, G from southern part. A, SW. ¼ SE. ¼ sec. 5, T. 8 N., R. 24 W.; B, SW. ¼ NW. ¼ sec. 2, T. 8 N., R. 24 W.; C, NE. ¼ SW. ¼ sec. 31, T. 9 N., R. 23 W.; D, SE. ¼ SE. ¼ sec. 17, T. 8 N., R. 24 W.; E, SE. ¼ SW. ¼ sec. 15, T. 8 N., R. 24 W.; F, NE. ¼ sec. 23, T. 8 N., R. 24 W.; G, SW. ¼ NE. ¼ sec. 24, T. 8 N., R. 24 W.

The east and west limits of workable coal in the Prairie View field can not be regarded as determined by the prospecting which has been done. Along the southern edge of the field, however, the drill holes show a thickness of 14 inches in sec. 24, T. 8 N., R. 24 W., east of which no workable coal was found. That the bed pinches out altogether farther east is indicated by prospecting near Knoxville in T. 8 N., R. 23 W., where several drill holes have passed through the Hartshorne horizon without finding any coal. In the western part of the district very few drill holes have been sunk to the coal horizon, and the inference made by the coal company that workable coal does not extend in that direction does not seem fully justified.

This district is undeveloped except for these drill holes, and no coal has been mined except for local use. The field is not accessible from any of the existing railroads, but could be reached by an extension of the Arkansas Central road, which now terminates at Paris. The distance would be not more than 15 miles.

RUSSELLVILLE DISTRICT.

The Russellville district lies at the extreme eastern end of the coal field as at present recognized, and includes two small basins of coal land, known as the Ouita basin, a few miles north of Russellville, and the Shinn basin, a few miles south of that place. Between Knoxville and Russellville the Hartshorne sandstone comes to the surface and crosses Arkansas River in a slight anticlinal flexure, so that these basins are not connected with the Spadra and Prairie View basins, although the coal is in the same horizon. A few miles west of Russellville, in the vicinity of London, there is an area of land containing something over one and one-half townships which is underlain by Spadra shale and Hartshorne sandstone, and, as will be seen from the geologic map, the Ouita basin is a northeastern extension of this larger basin. The Shinn basin is not connected with the London basin, a belt of Hartshorne sandstone intervening between them.

Ouita basin.—The coal lands in the Ouita basin, which are partially worked out, are estimated to have covered an area of approximately 2 square miles. Although the formation that carries the coal extends westward over the larger area of the London basin, coal has not been mined in that basin except in the area noted, and prospect wells a few miles farther west, near London, have revealed no coal. On the south side of the river opposite London, as much as 18 inches of coal have been found in a drill hole penetrating the Hartshorne horizon. The coal beds of Shinn and Ouita basins are evidently small remnants of a more extensive sheet of coal, which have been protected in synclinal folds, while the greater part has been eroded. This coal bed probably thins rapidly toward the northwest and pinches out entirely in a few miles, though it probably was once continuous along the south side of the river. The northern, eastern, and southern boundaries of the Ouita basin are determined by the outcrops of the Hartshorne sandstone, which dips under the coal land from all these directions. The coal in this field does not at any point lie very deep and has been mined from many small slopes, strip pits, and shafts which have now been abandoned and have caved in. Owing to the careless methods of mining probably much of the coal has been left in the ground and will be lost. Moreover, Illinois Bayou, a strong stream which heads in the Ozark Mountains, flows across the basin and has no doubt eroded a great deal of the shallow coal, so that much of the area included in the basin is not coal land.

The field includes one active mine as well as a number of small slopes and shafts that are occasionally worked for local supply. When it was examined all of the mines were shut down owing to the strike, and most of them were full of water, so that the coal bed was absolutely inaccessible. Although it was impossible to make measurements of the thickness of this coal bed, reports concerning it, believed to be reliable, indicate that the bed is without parting and has an average thickness of 28 inches. The roof and floor are shale. As reported by the Geological Survey of Arkansas the coal is about 26 inches thick and is overlain by 4 inches of bony or "wild" coal.[a]

Shinn basin.—The Shinn basin lies about 2 miles south of Russellville and includes approximately 2 square miles of coal land. Like the Ouita basin, this is bounded on all sides by outcrops of Hartshorne sandstone. On the south side of the basin this bed rock dips at a very high angle and is in some places slightly overturned, indicating that the basin has considerable depth. Shafts sunk for mining purposes show that its maximum depth from the surface probably exceeds 600 feet. Coal has been mined along the northern side of the basin for a great many years, where there are several abandoned slopes, but owing to the high pitch of the coal and its greater depth only a comparatively small amount of the area has been mined. The coal here is somewhat thicker than in the Ouita basin, ranging between 40 and 46 inches, with an 8 to 10 inch parting. Two thin coal beds, which are not worked, are reported several feet below, and a bed of coal a foot thick, lying above the main bed, has been passed through by some of the shafts. There are only three active mines in the basin, one of which has a shaft 480 feet deep and is the deepest coal mine in Arkansas.

The coals from both of these basins are classed as semianthracite. They command a somewhat higher price than the Spadra and other coals farther west, and are used almost exclusively for domestic purposes.

PHILPOTT DISTRICT.

The Philpott district lies in an isolated synclinal trough extending east and west through T. 10 N., Rs. 24, 25, and 26 W., north of the Coal Hill and Spadra fields. It includes a number of prospects and small mines which were operated before the larger mines along the railroad were opened. The coal produced was softer than the Spadra coal, and for local use formerly commanded a better price, since it ignites and burns more freely. Analyses show that it is semibituminous and of about the same grade as that at Coal Hill and Denning. (See table, p. 98.)

---

[a] Ann. Rept. Geol. Survey Arkansas, 1888, vol. 3, p. 34.

Two beds of coal, separated by from 600 to 800 feet of shale and shaly sandstone, occur here. The lower of these, known as the Pickartz bed, from the old Pickartz mine, is correlated on stratigraphic evidence with the Hartshorne bed. The shale and sandstone above it represent the Spadra and a part of the Fort Smith formation, and the upper coal bed, known as the Philpott coal, is near the Charleston coal horizon.

The Pickartz mine is situated in sec. 24, T. 10 N., R. 26 W., and the horizon of the coal has been traced eastward for a distance of nearly 18 miles, connecting with the coal which outcrops on Dicks Branch, sec. 10, T. 10 N., R. 23 W., and Minnow Creek, sec. 20, T. 10 N., R. 22 W. The position of this outcrop is shown on the geologic map, and from it the coal land extends northward in a synclinal trough 5 or 6 miles wide. The coal evidently passes under Mulberry Mountain, where the northern outcrop has not been determined. No mining has been done along this outcrop for many years.

The geologists of the Arkansas Survey reported the following section at the Pickartz mine:

Section of coal bed at Pickartz mine.

	Inches.
Coal	20 to 22
Shale	¼ to 2
Coal	1 to 4

The coal exposed at Dicks Branch measures 15 inches and at Minnow Creek 14 inches. So far as known there has been very little prospecting by deep drills to determine the amount of coal contained in this basin, though such an investigation would seem to be warranted by the showings already made. The upper bed, on which the old Moomaw and Philpott mines were located, is described in connection with the coal of the Charleston horizon.

OTHER LOCALITIES.

The most extensive and the best known areas in which the Hartshorne coal horizon occurs have now been described, but this horizon has been noted at a few other localities, where the coal is probably not present in minable quantity. One of the largest of these areas underlies Magazine Mountain, in T. 6 N., Rs. 24 and 25 W. Another smaller area lies about 10 miles northeast of Magazine Mountain. Nebo and Spring mountains, probably also Petit Jean Mountain, southeast of Russellville, and comparatively large areas north and east of Russellville, are capped with Hartshorne sandstone, but in all these the overlying rocks in which the coal is contained have probably been eroded away. In the region north of the district investigated there may be areas covered by Hartshorne sandstone and some of the overlying rocks, in which some Hartshorne coal may be found, but they are not known at present.

COALS OF THE COAL RIDGE OR CHARLESTON HORIZON.

The Fort Smith formation near its upper part contains one or more coal beds which have been mined for local supply at many places in the Arkansas field. These coals lie from 800 to 900 feet stratigraphically above the Hartshorne horizon and are nowhere more than 3 feet thick, generally being too thin for mining except from strip pits. Owing to the erosion of intervening areas it has been impossible to correlate these upper beds in different districts by continuous exposures, and though no individual coal bed at this horizon was probably ever continuous over the whole Arkansas coal field, it is believed that they are all within 100 feet of the same horizon. Coals at this horizon have been mined locally near Fort Smith, Central, Charleston, Caulksville, Alma, and in the Philpott basin. Their outcrops have been seen in many other places. The area covered by rocks of this horizon is indicated on the geologic map, Pl. VI. In general, the coal is of good quality and, as compared with Hartshorne coal, relatively free from ash, though on weathering it is often coated with white efflorescence. Graphic sections of coal beds of this horizon are shown in fig. 27.

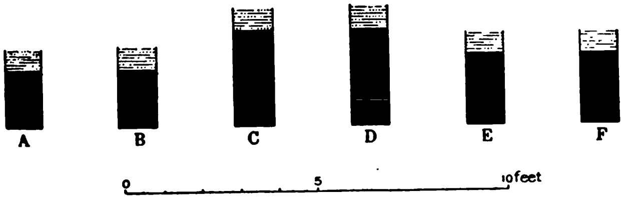


FIG. 27.—Characteristic sections of coal bed at Charleston horizon. A, Strip pit at Central, sec. 1, T. 7 N., R. 29 W.; B, slope under Coal Ridge, sec. 20, T. 7 N., R. 29 W.; C, Carters slope near Charleston, sec. 17, T. 7 N., R. 28 W.; D, prospect in bank of Big Creek, sec. 19, T. 7 N., R. 27 W.; E, Moomaw shaft near Ozark, sec. 22, T. 10 N., R. 26 W.; F, Philpott shaft, sec. 20, T. 10 N., R. 25 W.

CHARLESTON DISTRICT.

These coals are best exposed in the vicinity of Charleston, Franklin County, where the bed has been worked by stripping at many places indicated on the geologic map. In general, they have sandstone or sandy shale roofs and floors. The rocks overlying the coals contain at some places an abundance of fossil plants, which have already been described. (See report on paleobotany, pp. 24-31.) The coals are best exposed and were first examined in the west end of Coal Ridge, in sec. 15, T. 7 N., R. 30 W., 2 miles north of Auburn, where they occur in a group of thin sandstones with intervening sandy shale. The outcrops of the inclosing rocks form two ridges, known as Grand Ridge and Coal Ridge. The sandstone of Grand Ridge is estimated to be about 800 feet above the Hartshorne sandstone and 150 feet below the sandstone forming Coal Ridge, which is the upper bed of the Fort Smith formation. Coal has been mined here from a succession of small slopes on a bed about 100 feet below the sandstone forming Coal Ridge. It has a thickness of 18 inches without partings. An analysis of a sample (U. S. G. S. No. 13) taken at this horizon is given in the table (p. 98). About 60 feet above the bed mined there is a smaller bed, which is of no importance here but is probably of greater thickness elsewhere, and it is probably true that some of the many outcrops near Charleston represent this small upper bed, while others represent the lower.

In sec. 27, T. 6 N., R. 30 W., about 1 mile south of Auburn, an old strip pit, which was full of water at the time of examination, probably represents the upper one of these two beds. The coal here shows a tendency to break into cubical blocks and is coated with a white efflorescence. Its thickness was not measured, but the coal has been mined for local purposes for many years, and the opening is mentioned in the report of the Arkansas State Survey under the name Bean pit. Coal has also been obtained in the bed of Big Creek from an opening called the Langston pit, 1 mile south of the Bean pit, but the locality was not examined. The bed worked here probably corresponds with that mined at Coal Ridge north of Auburn.

East and north of Charleston there are many openings on one or the other of these beds, which will not require description in detail, their positions being shown on the geologic map. It is probable that there are still some large areas of land which can be mined by stripping in the region, but the topographic maps at hand and the time available for the work were not sufficient to define them. Two miles east of Charleston, on the Carter place, there is a new slope from which more or less coal is taken every year. It was full of water when examined, but the coal is reported to be 3 feet thick.

The same coal is probably represented in an old pit on sec. 3, T. 7 N., R. 27 W., 1 mile east of the town of Caulksville, where it is reported to be only 13 or 14 inches thick.

BONANZA AND JENNY LIND DISTRICT.

Coal of the same horizon outcrops at a number of places between Charleston and Fort Smith, the best known of which is on sec. 1, T. 7 N., R. 31 W., near Central, where there are several strip pits, small shafts, and slopes. The bed has a thickness of about 20 inches without parting. The coal has a cubical fracture, and after mining becomes coated with a white efflorescence. The same coal has been penetrated by wells at a number of points in the region southwest of Central, and has been mined from strip pits at Little Vache Grasse Creek and probably at other points.

The coal at the old Herman mine, in sec. 1, T. 8 N., R. 22 W., near Fort Smith, is probably also at this horizon. It is said to have been worked before and during the civil war and is noted in the Arkansas Survey reports. When the old workings were examined only one exposure, revealing 10 inches of good coal overlain by 1 foot of "bony" coal, was found. The bed is contained in sandy shale resembling that near Charleston.

VAN BUREN AND ALMA DISTRICT.

Coal of probably the same horizon outcrops at several points on the north side of the river near Alma, the thickness of the bed nowhere exceeding 18 inches and averaging 9 or 10 inches. At the Sullivant pit, in sec. 13, T. 9 N., R. 31 W., the coal measures 13 inches, and at the Graves pit in sec. 33, T. 9 N., R. 30 W., it measures 18 inches. Analyses of samples from these pits made by the Geological Survey of Arkansas (11 and 16 in table, p. 88) show that the coal is semibituminous. The same bed, perhaps, outcrops on Arkansas River at Moores Rock, in T. 8 N., R. 30 W., and it has probably also been found in wells at Van Buren. None of these openings expose a coal of workable thickness.

HUNTINGTON DISTRICT.

The same coal bed is probably exposed in Sugarloaf and Poteau mountains. It outcrops at the base of the Sugarloaf Mountains near the gap, where old excavations show that it has been opened, though no reports as to its thickness were obtained. The accidental exposures seen do not indicate that it is sufficiently thick to be of commercial value. A bed which may correspond with this is exposed at the Noblet pit, in sec. 31, T. 4 N., R. 32 W., on Poteau Mountain, where it is reported to consist of four thin benches aggregating 31 inches.[a]

PARIS DISTRICT.

At Paris this horizon is from 200 to 400 feet below the surface, and its outcrops north and south of the Paris basin have not been seen. In the Prairie View region, however, a coal bed 9 or 10 inches thick at about the proper distance above the horizon of the Hartshorne coal has been examined at a number of localities, which are noted on the geologic map. In no place has it been found to be of sufficient thickness to give it economic value under present conditions.

---

[a] *Ann. Rept.* Geol. Survey Arkansas, vol. 3, 1888, p. 19.

SPADRA DISTRICT.

A number of small coal beds, none of which are of economic importance and which correspond closely in stratigraphic position with the Charleston horizon, outcrop in the vicinity of Cabin Creek east of Clarksville. Although the detail of the stratigraphic succession of these beds has not been closely determined, they are regarded as corresponding approximately with the group of beds represented at Charleston.

PHILPOTT DISTRICT.

The bed mined at the old Philpott and Moomaw openings, in T. 10 N., R. 26 W., also seems to correspond approximately in stratigraphic position with the Charleston bed, though the interval between it and the Hartshorne may be as small as 600 feet. This coal lies in a synclinal basin about 4 miles long by 2 miles wide in which the rocks dip at low angles, and the coal is nowhere very deep. At the Philpott slope, sec. 20, T. 10 N., R. 25 W., the bed is from 18 to 22 inches thick, without partings, and a similar thickness is reported from other openings in the basin. The coal is semibituminous. Analyses of samples taken by the Arkansas Geological Survey indicate that it is comparatively low in ash and that it is chemically of a somewhat higher grade than the coal from the Pickartz bed.[a] Most of the product of one or two small mines is sold for domestic use at Ozark, to which place it is hauled by wagons. The eastern boundary of this basin has not been definitely determined, though the stratigraphy indicates that it can not extend far beyond the limit stated above.

Although the bed is comparatively thin, it seems to be well adapted to "long wall" mining, which has not yet been attempted, and all the coal contained will doubtless ultimately be available.

A similar small basin containing this coal doubtless underlies Mulberry Mountain, a few miles farther north, where no coal has been mined and no investigations were made by the United States Geological Survey party.

COALS OF THE PARIS HORIZON.

The horizon of the Paris coal is from 1,000 to 1,200 feet above the Hartshorne horizon. Stratigraphically it is about midway between the top and the bottom of the Paris formation. At the type locality near Paris the coal bed is overlain by shaly sandstone and underlain by sandy shale. A few inches of draw slate generally lies above the coal and at places some fire clay lies between it and the sandy shale floor. The bed varies in thickness from 2 to nearly 3 feet where it is worked. Near Paris the outcrop of the bed has been traced around the margin of the basin in which Short Mountain and Little Short Mountain are situated, as is shown by the geologic map.

---

[a] Ann. Rept. Geol. Survey Arkansas, 1888, vol. 3, p. 43.

The whole area underlain by this coal does not exceed 8 square miles, and in its western part the bed is probably too thin for mining. The coal has a bright luster and a rather indefinite cubical fracture. Chemically it is semibituminous and somewhat higher in hydrocarbon than the average Hartshorne coals in the same region. (See fig. 28, p. 85, and table of analyses, p. 98.) It is sold principally for domestic use. All the coal mined is hand picked or forked, the slack being left in the gob.

Outside of the Paris district this coal horizon is represented only in the vicinity of Potato Hill, where a coal bed provisionally correlated with it has been mined by stripping at several localities, though its thickness is not great enough at any opening to be of commercial importance. West of Potato Hill, in sec. 23, T. 6 N., R. 27 W., the coal is exposed in a strip pit which has been worked for local supply within the last year. The pit was full of water when examined, so that the coal could not be measured, but its thickness is reported to be about 14 inches. The same coal outcrops in several localities near Pine Hill, but it is not mined to any extent, and its thickness is not great enough to warrant development.

Except in these two areas the coal of this horizon has not been examined in Arkansas. It should outcrop in Sugarloaf, Poteau, and Magazine mountains, and it has probably been seen by prospectors and others in each of the two former localities, though it has not been reported from the latter. On stratigraphic and paleobotanic evidence it is provisionally correlated with the McAlester coal of Indian Territory. (See report on fossil plants, pp. 24–31.)

COALS IN THE ATOKA FORMATION.

Coal beds have been reported from many localities in the series of shales and sandstones underlying the Hartshorne, to which the name Atoka formation is applied. These lower coal beds are not continuous for any great distance and are thin, except in small areas. The investigation of the rocks below the Hartshorne horizon has been too limited and too unsystematic to enable the correlation of such coal beds with one another, and they will be described by localities without reference to horizons. In the western part of the field such coal has been reported at only one locality, in the center of the Backbone anticline, about 2 miles northeast of Hackett. The coal bed here lies between 500 and 1,000 feet below the Hartshorne sandstone and is not believed to be more than a few inches thick. Coal is also reported by the Geological Survey[a] of Arkansas in the neighborhood of Booneville, on Fletcher Creek, the locality being known as the Carlan drift. Although not examined, this coal is believed to be several hundred feet below the Hartshorne sandstone.

---

[a] *Ann. Rept.* Geol. Survey Arkansas, 1888, vol. 3, pp. 23, 59, and 80.

A small bed of coal which has been mined from strip pits for local use also outcrops on a bench on the north side of Rich Mountain 4 miles southwest of Ellsworth, in T. 7 N., R. 24 W. It was impossible to make an examination of this coal bed, as the pit has not been worked for several years and had caved in. The coal here is estimated to be about 300 to 400 feet below the Hartshorne sandstone. What is believed to be the same bed of coal has been penetrated by two drill holes in the vicinity of Shoal Creek, in T. 7 N., R. 23 W. It is 400 feet below the Hartshorne coal horizon, and one of the wells shows that it is nearly 4 feet thick, but is divided by shale partings. Where penetrated by the other well this bed is somewhat thinner.

Coal beds of horizons below the Hartshorne outcrop at several localities south of Shinn basin, in the Russellville district. The rocks here strike approximately east and west and dip northward under Shinn basin at high angles. There is some evidence of a fault here, making it difficult to estimate the interval between these coals and the Hartshorne horizon. It is probable that two beds are represented here, one about 400, the other from 800 to 1,000 feet below the Hartshorne. Prospecting with diamond drills was in progress here during the summer of 1906, though at the time the region was visited no coal thick enough to work had been discovered.

In the region south and southeast of Dardanelle the same beds have been mined occasionally since the civil war. Some old excavations in sec. 35, T. 6 N., R. 21 W., north of Centerville, expose from 18 to 20 inches of coal at the outcrop. Several drill holes which have been sunk on this bed indicate that it has a maximum thickness of a little less than 3 feet. The structure here indicates that this bed should dip north into an extensive synclinal basin, and should crop out again a few miles south of Dardanelle. Its northern outcrop, however, has not been recognized. Near the center of this syncline a higher bed of coal has been discovered in one or two wells and is reported to have a thickness of 14 to 15 inches. These beds are estimated to be about 400 feet and 800 feet, respectively, below the Hartshorne. What is probably the equivalent of the lower of these beds has been mined near Chickalah, south of Mount Nebo, and its occurrence west of Spring Mountain has been noted in the report of the Geological Survey of Arkansas, neither of which localities were examined. A thin coal that must also belong to one of the lower horizons has been reported near Atkins in T. 7 N., R. 18 W., and also near Galla Rock in T. 6 N., R. 20 W.

A coal bed 1 foot thick in one of these lower horizons outcrops and has been mined in the NE. ¼ sec. 24, T. 9 N., R. 26 W., in the Coal Hill district just north of the Coal Hill fault. This bed has been estimated to be about 100 feet below the base of the Hartshorne sandstone. Another similar bed 500 feet below the Hartshorne coal horizon has been penetrated by a drill hole in sec. 20, T. 9 N., R. 26 W., northwest of Denning, where it is reported to be 5 feet thick. Between Altus and Ozark there are several outcrops of a coal bed less than 1 foot thick, which is probably near the same horizon.

A bed that is possibly slightly lower outcrops and has been prospected at the base of the sandstone on which the town of Ozark is built, and a similar coal outcrops south of Arkansas River opposite Ozark. The geologic work around Ozark has not been sufficient to demonstrate whether or not these various outcrops of coal can be correlated with one another. The beds vary greatly in thickness at different points, but are characterized by great irregularity and impurity, more than half of the bed usually being bone or black shale. A dirty coal bed somewhat resembling these, but more than 2 feet thick, has been reported from drill holes near the river several miles above Ozark. This bed, if present as reported, must necessarily be below the Hartshorne sandstone, and the results of prospecting thus far indicate that it has no economic value.

Drill holes that have been sunk to great depths in the neighborhood of Alma and Van Buren disclose no coal beds below the Hartshorne horizon. The same may be said of the drill holes in the vicinity of Fort Smith. Small coal beds of no economic value, which have not been correlated with each other nor with the beds herein described, are reported at several places in the large area underlain by Winslow sandstone north of the western part of the coal field, which has been examined in detail for the Winslow folio. All the evidence now available regarding coal below the Hartshorne horizon indicates that these coals are of greater thickness in the eastern part of the field than in the western, where they are practically absent.

From present indications further investigation of such beds in the vicinity of Russellville and Dardanelle is certainly justified and will probably result in extending the boundaries of the coal field as at present defined.

CHARACTER OF THE COAL.

PHYSICAL CHARACTERISTICS.

Most of the coals of Arkansas have a bright luster when freshly mined, though parts of some of the beds at a few places are described as dull. They generally present little evidence of stratification and seldom any cleavage parallel to the bedding, but the vertical cleavage or "cleat" is complex and somewhat indefinite. Except at one or two mines, the cleat is an unimportant factor in mining, entries and rooms being driven without respect to any inherent structure, though the many cleavage planes affect the value of the coal by making it fragile.

All of the coals are more or less brittle and friable and as mined yield from 10 to 40 per cent of fine slack, the percentage of which is *probably an index to* the relative hardness of the coal in different parts of the field. For example, mine-run coal in the Jenny Lind, Greenwood, and Huntington districts, at the west end of the field, contains from 20 to 35 per cent slack, while that at Russellville, in the east end of the field, contains not more than 10 per cent. This difference, however, is due in part to the method of mining. Where the coal is mined by blasting or shooting off the solid, the percentage of slack is higher than that produced by hand or pick mining. The coals at Spadra and at Russellville seem to be of nearly equal hardness, but a much higher per cent of slack is produced in the former district owing to the use of powder in mining, the coal in the latter district being won by pick mining.

All of these coals are of comparatively high specific gravity, ranging from 1.29 to 1.49 and averaging about 1.35, which is equal to the average of Pennsylvania bituminous coals of better grade. Although hardness and specific gravity are not indicated by the results of chemical analysis, they are of the utmost importance in determining the uses to which any particular coal is best adapted. For example, the hard coals, even though they may produce a less amount of heat, are better adapted to domestic use than the soft ones. Coals of high specific gravity, other things being equal, are better adapted to use under locomotive and marine boilers than light ones, since a greater amount of fuel can be stored in the same space, and the heavier coals also give better results under forced draft. The relative hardness and specific gravity of different coals are doubtless due to a number of causes, the two more important probably being the degree of alteration of the original woody material of which it is composed and the amount of impurity contained in the coal as ash. One of the chief advantages of the Arkansas coals is that in burning they produce relatively little smoke.

CLASSIFICATION OF THE COAL.

The classification of coal into the various grades recognized in trade, based primarily on their physical properties and their adaptability to particular uses, coincides approximately with a classification based on the degree of alteration from their original woody character, coal of the lowest grade being lignite, while the most highly metamorphosed coal is anthracite. This classification is indicated by proximate chemical analyses showing the proportions of fixed carbon, volatile matter, water, and ash, which they contain. The method of analysis is as follows:

A small amount of coal is crushed and reduced to fine powder, weighed, and then dried at a temperature somewhat above the boiling point, which drives off the greater part of the moisture. It is again weighed and the difference in the two weights is taken as that of the *water contained* in the coal. The sample is then placed in a tightly covered crucible and heated in a Bunsen flame until all the gases are driven off and burned around the edges of the cover. It is then cooled and again weighed, the loss in weight being taken as the amount of volatile matter. The residue in the crucible now consists only of fixed carbon and ash. In the coking coals this residue will be fused into a solid mass, but in others it remains as an incoherent powder. It is then heated over the flame in an uncovered crucible until all of the carbon is burned and only ash remains, when it is again weighed and the difference between this weight and the preceding is taken as the fixed carbon and the weight of the residue as ash.

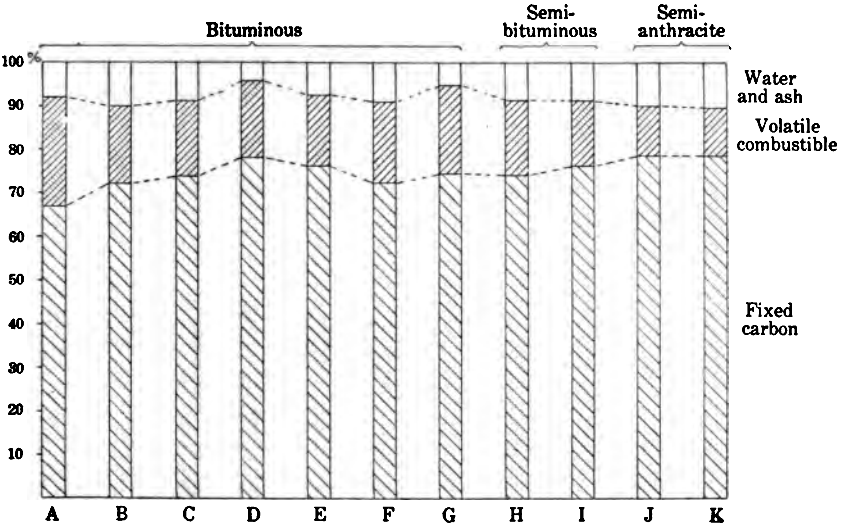


FIG. 28.—Diagram showing the composition of coals from different parts of the Arkansas field. A, coal from Bates district; B, Huntington coal; C, Bonanza and Jenny Lind coal; D, Hackett coal; E, Montreal, Midland, and Burma coal; F, Greenwood coal; G, Charleston coal; H, Paris coal; I, Coal Hill and Denning coal; J, Spadra coal; K, Russellville coal.

Such analyses are easily and quickly made and are usually sufficient for classification purposes when taken in connection with the obvious physical properties of the coal. Coals of higher grades are well differentiated by the relation between the percentages of fixed carbon and of volatile matter they contain. This relation is called the fuel ratio.

In the original Pennsylvania classification proposed by Persifor Frazer, jr.,[a] anthracite coals have fuel ratios above 12, semianthracite coals from 12 to 8, semibituminous coals from 8 to 5, and bituminous coals from 5 to 1. Generally, however, the limits of the various groups as understood in the trade are somewhat lower.[b] Arkansas anthracite or semianthracite coals have fuel ratios from 8½ to 6½ and the semibituminous coals from 6½ to 4½. As graded by this standard the Arkansas coals range from bituminous to semianthracite; those in the district south of Poteau Mountain are bituminous, their fuel ratios averaging about 3. The coals north of Poteau Mountain also, in the western part of the field, are near the dividing line between bituminous and semibituminous, and may perhaps be regarded as semibituminous, their fuel ratios averaging nearly 5; those in the Coal Hill-Denning and Paris districts are also semibituminous and of somewhat higher grade, while the coals in the Spadra and Russellville districts are semianthracite, their fuel ratios averaging above 7. The relative grades of the coals in the various districts are shown graphically in the group of diagrams forming fig. 28, those of the highest grade, from the eastern part of the field, being at the right, and those of lower grades, from the southwestern part, at the left of the figure.

---

[a] Trans. Am. Inst. Min. Eng., vol. 6, p. 430; also Rept. MM, Second Geol. Survey Pennsylvania, 1879.

[b] Report on the coals of Maryland: Maryland Geol. Survey, vol. 5, 1905. p. 239. Campbell, M. R., Character of Yampa coals: Bull. U. S. Geol. Survey No. 297, 1906, p. 87.

A somewhat more satisfactory determination of the character of the coal is obtained from ultimate analyses, in which, by more elaborate chemical methods, the exact amounts of carbon, hydrogen, oxygen, sulphur, and other elements are determined.

EFFICIENCY OF THE COAL.

The relative efficiencies of various coals are determined in the laboratories by burning them in an apparatus called a calorimeter, in which the amount of heat developed by the total combustion of a given weight of the coal is accurately measured, and the results of such determinations are stated both in pound calories and in British thermal units, the former being the number of pounds of water, at maximum density, whose temperature can be raised 1 degree centigrade by the combustion of 1 pound of coal, the latter representing the number of pounds of water which will be raised 1° F. and being equal to nine-fifths of the former.

Calorific values of coal can be calculated very closely from ultimate analyses by Dulong's formula:

Heat value per pound, B. t. u. $= 146\ C + 620\ (H - \frac{O}{8})$, in which C, H, and O are, respectively, the percentages of carbon, hydrogen, and oxygen.

Proximate analyses give only the roughest approximations to the heat value of coals, owing to the very indefinite composition of the so-called volatile matter. Proximate analyses of coals within any given district or field, however, vary but slightly from one another, and it may be expected that the volatile combustible matter will have about the same relative value, so that if a few calorific determinations have been made the heat values of the others can be roughly estimated from proximate analyses. The efficiency of the coal from various parts of the field will depend mainly on its freedom from impurities in the form of ash.

Calorific determinations which have been made of Arkansas coals give an average value of 207 B. t. u. for each per cent of volatile matter and 146 B. t. u. for each per cent of fixed carbon. The heat value, in B. t. u., can therefore be roughly estimated from the proximate analyses as equal to 146 times the percentage of fixed carbon plus 207 times the percentage of volatile matter. The relative heat-producing values of the coals in the various parts of the field under discussion are shown graphically in fig. 29, from which it will be seen that the semianthracites of the eastern districts are slightly lower in efficiency than the semibituminous coals to the west.

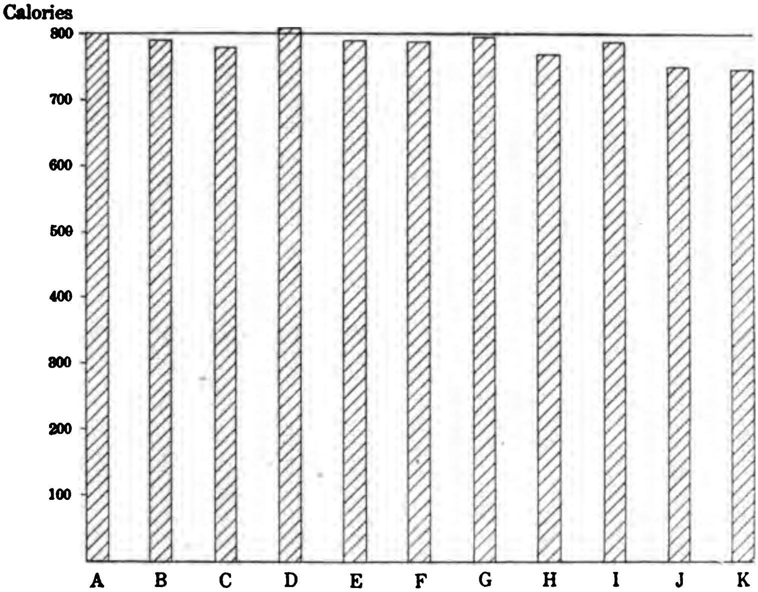


FIG. 29.—Diagram showing relative calorific values of coals from different parts of the Arkansas field. A, coal from Bates district; B, Huntington coal; C, Bonanza and Jenny Lind coal; D, Hackett coal; E, Montreal, Midland, and Burma coal; F, Greenwood coal; G, Charleston coal; H, Paris coal; I, Coal Hill and Denning coal; J, Spadra coal; K, Russellville coal.

SPECIAL TESTS AND ANALYSES.

ANALYSES MADE BY ARKANSAS GEOLOGICAL SURVEY.

Samples of coal from twenty-seven localities were collected by the Geological Survey of Arkansas, and proximate analyses, including specific-gravity determinations made by the chemists of the Survey, were published in their preliminary report.[a] No uniform method was followed in collecting these samples, some being taken from working faces of mines, while others were from carloads or from piles of coal left on the dumps. They can hardly be regarded, therefore, as strictly representative of the coal beds sampled. Moreover, the method of analyses is not stated in the report.

---

[a] Ann. Rept. Geol. Survey Arkansas, 1888, vol. 3, p. 43.

Proximate analyses of Arkansas coals made by the Geological Survey of Arkansas.

[Analyses by Dr. R. N. Brackett, assisted by Mr. J. P. Smith.[a]]

Sample No.	Name of pit or mine.	Nearest town.	Location.	Moisture.	Volatile matter.	Fixed carbon.	Ash.	Sulphur.	Fuel ratio.
1	Carnall's drift	Oak Valley	S. 18, T. 7 N., R. 30 W.	5.26	17.66	61.98	13.62	1.49	3.51
2	Page's pit	Greenwood	S. 19, T. 6 N., R. 30 W.	.85	16.39	78.22	3.30	1.24	4.77
3	Baxley's pit	Paris	S. 35, T. 8 N., R. 26 W.	1.23	15.75	75.34	5.28	2.40	4.79
4	Hackett Cy. shaft	Hackett	S. 22, T. 6 N., R. 32 W.	.85	14.916	73.87	9.04	1.32	4.95
5	Pickartz drift	Ozark	S. 26, T. 10 N., R. 26 W.	.70	15.88	79.00	3.56	.86	4.97
6	Huntington slope	Huntington	S. 24, T. 5 N., R. 31 W.	.93	15.55	77.54	4.85	1.43	4.99
7	Claiborne's pit	Hartford	S. 17, T. 4 N., R. 31 W.	.94	15.54	78.36	4.01	1.15	5.04
8	Lewis's pit	Alston	S. 4, T. 9 N., R. 28 W.	.88	15.23	77.20	4.24	2.45	5.07
9	McConnel's shaft	Greenwood	S. 32, T. 7 N., R. 30 W.	.600	15.38	78.30	4.58	1.14	5.09
10	Greenwood shaft	do	S. 12, T. 6 N., R. 31 W.	.82	14.87	75.82	5.97	2.52	5.10
11	Sullivant	Alma	S. 13, T. 9 N., R. 31 W.	.76	12.95	67.13	14.20	4.96	5.19
12	Bocquin	Jenny Lind	S. 31, T. 7 N., R. 31 W.	.75	14.98	77.87	5.00	1.40	5.20
13	Gwyn's drift	Hartford	S. 14, T. 4 N., R. 32 W.	.89	14.58	77.09	6.25	1.19	5.29
14	Carlan's slope	Booneville	S. 22, T. 5 N., R. 28 W.	.85	14.67	78.40	4.71	1.37	5.34
15	Moomaw's pit	Ozark	S. 22, T. 10 N., R. 26 W.	.66	14.89	79.81	3.27	1.37	5.36
16	Graves drift	Alma	S. 33, T. 9 N., R. 30 W.	.57	13.90	75.07	7.61	2.85	5.40
17	Petty's slope	Jenny Lind	S. 32, T. 7 N., R. 31 W.	1.78	13.33	76.23	7.05	1.62	5.72
18	Philpott shaft	Coal Hill	S. 20, T. 10 N., R. 25 W.	.87	14.13	80.92	3.09	.99	5.73
19	Watt's slope	Central	S. 13, T. 7 N., R. 31 W.	.74	12.62	72.61	9.97	4.07	5.75
20	Felker slope	Coal Hill	S. 24, T. 9 N., R. 26 W.	1.13	13.21	81.28	3.22	1.16	6.15
21	Ouita slope	Russellville	S. 30, T. 8 N., R. 20 W.	.98	12.20	76.82	8.17	1.83	6.29
22	Eureka shaft	Spadra	S. 23, T. 9 N., R. 24 W.	1.10	11.28	72.84	12.04	2.75	6.46
23	Coal Hill shaft	Coal Hill	S. 20, T. 9 N., R. 25 W.	1.02	10.84	76.12	8.35	3.67	7.02
24	Allister slope	do	S. 24, T. 9 N., R. 26 W.	1.18	10.48	76.49	8.32	3.53	7.30
25	Mason drift	Clarksville	S. 27, T. 10 N., R. 23 W.	1.12	11.01	80.86	5.86	1.16	7.34
26	Harkreader's well	do	S. 34, T. 10 N., R. 24 W.	1.56	10.35	78.91	6.31	2.87	7.62
27	Shinn slope	Russellville	S. 21, T. 7 N., R. 20 W.	1.06	8.41	75.43	11.75	3.35	8.96

Proximate analyses of Arkansas coals furnished by mining companies.

	W. C. & M. Co.[b]	Jenny Lind		0.49	13.64	76.73	7.12		5.63
	P. C. C. Co.[c]	Huntington		1.33	14.03	77.83	5.63	1.33	5.55
	W. C. & M. Co.[b]	Denning		1.07	11.21	78.01	8.13		6.96
	A. A. Co.[d]	Prairie View	S. 23, T. 8 N., R. 24 W.	1.1	14.6	73.2	9.7	1.4	5.01
	Do	do	S. 31, T. 9 N., R. 23 W.	.6	10.7	77.5	10.1	1.1	7.24
	Do	do	S. 12, T. 8 N., R. 24 W.	.6	10.1	75.4	11	2.9	7.46

[a] Ann. Rept. Geol. Survey Arkansas, 1888, vol. 3, p. 43.

[b] Western Coal and Mining Co., St. Louis Sampling and Testing Works, analyst, 1897. Twenty-second Ann. Rept. U. S. Geol. Survey, pt. 3, 1902, p. 398.

[c] Prairie Creek Coal Co., analyses by Bureau of Equipment, Navy Department, Washington, D. C.

[d] Arkansas Anthracite Co., Little Rock. Prospectus.

Many analyses of Arkansas coal from various localities have also been made by commercial assayers working for private parties, some of which have been reported to members of the Geological Survey. Like those made by the State Survey, the private analyses are not uniform in either the method of sampling or the method of analysis; but since many of the localities represented were not duplicated by the present survey, it seems advisable to republish them. All such analyses at hand, including those made by the State Survey and by private assayers, are presented in the above table.

FUEL-TESTING PLANT SAMPLES.

The agents of the United States Geological Survey fuel-testing plant, at the Louisiana Purchase Exposition, in 1904 and 1905, collected four sets of samples representing the Arkansas coal field. Each set included two samples cut from working faces in the mine and a carload lot representing the commercial product. They also collected mine samples from four other mines and obtained several carloads of slack from various localities for experimental work.

In taking mine samples the following method was invariably observed:[a]

> After the face of the coal was cleaned of any weathered coal or powder smoke a cut was made across the face of the coal from roof to floor, including all of the benches of coal mined and such impurities as were not removed in ordinary work. This cut was about 3 inches wide and 1 inch deep. The coal obtained from it, amounting to 25 or 30 pounds, was caught upon an oilcloth blanket spread upon the floor of the mine, so as to protect the sample from water and from including any shale or clay fragments.
>
> The coal composing the sample was then pulverized and quartered down according to the generally accepted rules for preparing samples until a quart sample was obtained, with the particles of coal reduced to a size not much greater than one-fourth inch in diameter. The sample was placed in an air-tight galvanized-iron can having a screw top, and the can was hermetically sealed by screwing the top down tight and covering the joint with tire tape. The can containing the sample was then mailed to the testing plant, and in almost all cases it reached its destination within two or three days of the date of sampling in the mine.

The four complete sets of samples from this field are described in the report of the fuel-testing plant as Arkansas Nos. 1, 2, 3, and 5, and they will be so designated in this report.

Arkansas No. 1, collected by M. R. Campbell and John W. Groves, represents the coal locally known as the Huntington coal. It is in the horizon of the Hartshorne coal of Indian Territory and is probably continuous with the Hartshorne bed. Sample A, laboratory No. 1046, was taken at a point where the coal bed has a thickness of 7 feet 7 inches, with two partings, one of black shale 5 inches, the other of shale and coal 10 inches thick. Sample B, laboratory No. 1045, represents the coal where the bed is 6 feet 6 inches thick, with two partings, one of black shale 5 inches, the other of shale and coal 1 foot thick. Sample C, laboratory No. 1114, represents as nearly as possible a carload containing 44 short tons of engine coal which was shipped to St. Louis to be tested.

Arkansas No. 2, sampled by M. R. Campbell and John W. Groves, represents the coal bed that is known locally as the "Jenny Lind vein." This bed is in the Hartshorne horizon, and is equivalent to if not identical with, the bed mined at Huntington, Ark., and Hartshorne, Ind. T. Sample A, laboratory No. 1053, represents the coal where the bed is 3 feet 8½ inches thick, with a shale parting 1½ inches thick near the center. Sample B, laboratory No. 1049, represents the bed where it is 3 feet 8 inches thick, with a similar parting 2½ inches thick. Sample C, laboratory No. 1160, represents, as near as possible, a carload shipped to St. Louis for testing.

Arkansas No. 3, sampled by John W. Groves, represents the coal mined at Jenny Lind. At the point where sample A, laboratory

---

[a] Campbell, M. R., Field work, in Preliminary report on the operations of the coal-testing plant of the United States Geological Survey: Bull. U. S. Geol. Survey No. 261, 1905, pp. 19-20.

No. 1115, was taken the bed has a thickness of 4 feet 8 inches, with a 3½-inch shale parting near the center. Sample B, laboratory No. 1118, represents the same bed where its thickness is 3 feet 9 inches, with a 3-inch parting. Sample C, laboratory No. 1296, represents a carload sent to St. Louis for testing.

Arkansas No. 4 was a carload sample of slack for briquetting tests, representing four mines near Denning.

Arkansas No. 5, collected by John W. Groves, 1½ miles west of Coal Hill, is from a bed locally known as the Denning bed. The coal bed is in the Hartshorne horizon, and is probably identical with the Hartshorne bed of Indian Territory. Sample A, laboratory No. 1130, was cut where the coal is 3 feet 9 inches thick, with a 5½-inch parting of shale and coal near the center. Sample B, laboratory No. 1131, was cut where the bed is 3 feet 9 inches and the shale parting 7 inches thick. Sample C, laboratory No. 1331, represents a carload consisting of about 20 short tons of lump coal over a 1.8-inch bar screen and about 20 tons of slack or coal that passed through this screen.

Arkansas No. 6, laboratory No. 1542, was a car sample of slack mined at Jenny Lind and was shipped to the fuel-testing plant by the operator for special tests in briquetting and coking.

Eight special samples taken for chemical tests from mines not represented by carload lots are as follows:

Laboratory numbers 1030 and 1031 represent a mine in sec. 36, T. 9 N., R. 31 W., near Jenny Lind. They were collected by John W. Groves. The same mine is represented by sample No. 9, collected by the Geological Survey party.

Laboratory Nos. 1040 and 1042 represent a mine in sec. 22, T. 9 N., R. 26 W., near Denning. The bed is the same as that represented by the samples under Arkansas No. 5, and the coal measures 3 feet 7 inches and 4 feet 5 inches, respectively, at the two points where samples were cut.

Laboratory Nos. 1052 and 1054 represent a mine in sec. 13, T. 5 N., R. 32 W., near Midland. They were collected by J. Shober Burrows. The coal is without partings and measures, respectively, 2 feet 10 inches and 2 feet 9 inches at the points where the samples were cut.

Laboratory Nos. 1066 and 1068 represent a mine in sec. 1, T. 4 N., R. 32 W., south of Midland. The bed is in the Hartshorne horizon and is a western extension of that mined at Huntington. It measures 8 feet 7 inches and 8 feet 5 inches, respectively, at the two points sampled, but is divided by a parting into two benches, both of which are mined.

Twenty-six samples from various mines were taken by the United States Geological Survey party in the summer of 1906. The method of sampling was identical with that followed by the agents of the fuel-testing plant, except that usually only one sample was taken from each mine. These samples were numbered consecutively in the order in which they were collected and are as follows:

Sample No. 1, laboratory No. 3155, represents the coal at a strip pit near Burma in sec. 19, T. 5 N., R. 31 W. The bed mined is in the Hartshorne horizon and is regarded as equivalent to that mined at Hartshorne, Ind. T. The bed here is 3 feet 7 inches thick without partings. Sampled by C. D. Smith.

Sample No. 2, laboratory No. 3154, represents one of the working faces of a mine at Burma station in sec. 20, T. 5 N., R. 31 W. The bed is the same as that at the pit, represented by sample No. 1, laboratory No. 3155. It is 36 inches thick, has a hard sandstone roof and sandy shale floor, and is worked from a shaft about 60 feet deep. Sampled by C. D. Smith and A. J. Collier.

Sample No. 3, laboratory No. 3158, is from a mine near Burma station, in sec. 19, T. 5 N., R. 31 W. The coal bed has an average thickness of 36 inches and is the same as that of sample No. 2. It is overlain by a thick bed of hard sandstone, but in the western part of the workings shale of varying thickness intervenes between the coal and the sandstone. Sampled by C. D. Smith.

Sample No. 4, laboratory No. 3150, represents a mine in sec. 19, T. 5 N., R. 31 W., a short distance southeast of Montreal station on the St. Louis and San Francisco Railroad. The bed mined is the same as that at the Denman and Red Rock mines and is in the Hartshorne horizon, though the roof is shale. The sandstone lens, which constitutes the roof in the mines just mentioned, thins out and disappears before reaching this mine. The coal averages about 42 inches thick without partings. Sampled by C. D. Smith.

Sample No. 5, laboratory No. 3152, is from a mine located near Montreal station in sec. 13, T. 5 N., R. 32 W. The bed, which is the same as that just described, has an average thickness of 3 feet 4 inches. The sample was taken by C. D. Smith from one of the lowest entries in the slope.

Sample No. 6, laboratory No. 3156, is from a slope in sec. 19, T. 5 N., R. 31 W., near the line of the St. Louis and San Francisco Railroad. At this place the coal has been mined by stripping for half a mile or more along the outcrop and sample No. 1 was taken from a face exposed in the pits. Where the pitch of the coal has carried it to such a depth as to make strip mining impracticable, short slopes have been driven from the face as exposed. This sample was collected by C. D. Smith from the face in one of these slopes for comparison with sample No. 1, to determine the effect of weathering. The analyses of the two samples, 1 and 6, however, are nearly identical, and indicate that the coal is stable and only slightly affected by weathering.

Sample No. 7, laboratory No. 3148, is from a partially developed mine located about three-eighths of a mile northeast of Burma station. The coal is reached by a shaft about 25 feet deep, which pierces the hard sandstone lens that forms the roof of the Red Rock and Denman mines. The bed is not quite so thick as that in the Red Rock mine, and about 4 inches near the top is thrown out in mining. The coal which is hand-picked and sacked, is used for blacksmithing purposes and brings a somewhat higher price than the other coals of the district. Sampled by C. D. Smith.

Sample No. 8, laboratory No. 3157, represents the coal at a mine in sec. 18, T. 6 N., R. 31 W., about 2 miles east of Hackett. The bed is 32 inches thick without partings. It is reached by a shaft 60 feet deep. The sample was taken by Sidney Paige from a clean dry working face. This coal is in the eastern extension of the bed mined at Hackett, Ark., and at Panama, Ind. T., and is almost identical in character. At Greenwood, a few miles farther east, it is very much thicker, but is divided by partings.

Sample No. 9, laboratory No. 3153, represents the coal from a mine at Jenny Lind. The bed averages about 6 feet. The sample was taken by C. D. Smith from a working face near the end of one of the west entries. The mine was rather damp with surface water, though the face of the coal was not wet.

Sample No. 10, laboratory No. 3151, represents the coal in a mine 1 mile west of Jenny Lind. It is the same mine as is represented by the sample Arkansas No. 3, previously collected for the fuel-testing plant. The bed where the sample was collected contains 38 inches of coal separated into two benches by a parting of hard shale 14 inches from the floor. It was sampled by Sidney Paige.

Sample No. 11, laboratory No. 3173, represents a mine in sec. 12, T. 6 N., R. 30 W., near Greenwood. The bed varies in thickness from 4 feet to 7 feet and is separated into two benches by a parting of soft shale near the center, which varies from a fraction of an inch to 6 inches. The sample was taken by C. D. Smith from a working face in the lower part of the mine as far as possible from the outcrop.

Sample No. 12, laboratory No. 3175, represents the coal in a mine a few miles east of Greenwood. The total thickness of the bed is about 8 feet, 5 feet of which in one bench is mined. The sample was collected by C. D. Smith and represents the part mined.

Sample No. 13, laboratory No. 3218, represents a bed that has supplied coal for neighborhood use from a number of strip pits and other openings near Charleston. The bed is stratigraphically from 800 to 900 feet above the Hartshorne horizon and is provisionally correlated with that formerly worked near Caulksville, Central, Fort Smith, and other places. It is believed to be at about the same horizon as the Philpott bed north of Coal Hill, though the exact correlation of the latter is regarded as doubtful. It is described in *this report* as the Charleston bed, but is variously known locally as the Sky vein, Coal Ridge vein, etc. The sample, which is the only representative of the coal at this horizon, was taken by Sidney Paige from a small drift worked occasionally at the west end of Coal Ridge in sec. 20, T. 7 N., R. 29 W., a few miles north of Auburn. The face from which it was cut had probably been exposed to the air for several months. The bed has a thickness of 18 inches without partings.

Sample No. 14, laboratory No. 3174, is from a mine at Paris, Ark. The mine is located in sec. 10, T. 6 N., R. 26 W., and the coal bed is known and described in this report as the Paris coal. It is from 1,000 to 1,400 feet vertically above the Hartshorne coal and probably from 400 to 600 feet above the Charleston coal. The sample was taken from one of the working faces in the deepest part of the mine and represents a thickness of 26 inches without partings. The bed has a firm sandstone roof from which it is separated by half a foot or more of draw slate. It is underlain by a thin seam of fire clay and mining is done by undercutting.

Sample No. 15, laboratory No. 3177, represents a mine in the Shinn basin, south of Russellville, and was collected by C. D. Smith from a working face in the deepest part of the mine. The coal is reached by a shaft 70 feet deep, located in sec. 22, T. 7 N., R. 20 W. It varies in thickness from 30 to 36 inches. The bed is in the Hartshorne horizon and may be identical with that mined in the western part of the field at Huntington, Jenny Lind, and Greenwood.

Sample No. 16, laboratory No. 3176, from a mine in Shinn basin, south of Russellville, represents the same bed as sample No. 15. This is the deepest mine in Arkansas, the coal being reached by a 480-foot shaft. It is situated in sec. 21, T. 7 N., R. 20 W. The sample was collected by C. D. Smith from one of the working faces of the mine.

Sample No. 17, laboratory No. 3368, from a mine near Spadra, Ark., in the SW. ¼ sec. 14, T. 9 N., R. 24 W. The bed is 44 inches thick, with a parting of 3 inches or more near the middle. It is mined from a shaft 140 feet deep. The sample was cut by R. D. Mesler from one of the working faces of the mine.

Sample No. 18, laboratory No. 3369, is from the Brooks mine about 2 miles south of Clarksville in sec. 17, T. 9 N., R. 23 W. The coal bed is known as the Spadra bed and has a thickness of 34 inches with a 2-inch shale parting near the center. It is mined from a shaft 240 feet deep. The sample was taken by R. D. Mesler from one of the working faces of the mine.

Sample No. 19, laboratory No. 3370, is from a mine 2½ miles southwest of Coal Hill. The bed mined here is the same as that represented by the sample Arkansas No. 5, of the fuel-testing plant which was taken from a mine about 1½ miles to the west. Both of these are in the Hartshorne horizon and are probably identical with the bed mined at Bonanza and Huntington. This mine is a small one and was not shut down during the strike. The sample was taken from one of the working faces, where the bed is 3½ feet thick with a half-inch parting near the center.

Sample No. 20, laboratory No. 3371, is from a small mine at Center Cross about 2 miles west of Altus. The coal bed is in the Hartshorne horizon and is regarded as equivalent to the Coal Hill and Denning bed from which sample No. 19 was collected. It consists, however, of two beds of coal, each about 2 feet thick with 18 feet of sandy shale between them, which is probably equivalent to the parting found in the Coal Hill and Denning beds. In the Denning field the parting is known to increase locally to a thickness of 6 or 7 feet. Only the lower bench, about 25 inches thick, is mined, and it alone is represented in this sample, which is cut from a working face. The mine, however, is shallow, and the total cover over the coal where sampled does not exceed 25 feet. Sampled by R. D. Mesler and A. J. Collier.

Sample No. 21, laboratory No. 3372, is from a mine in sec. 30, T. 8 N., R. 31 W., on Massard Prairie about 5 miles from Fort Smith. The coal bed which is regarded as equivalent to the bed mined at Jenny Lind and Bonanza, is from 27 to 30 inches thick, with a shale parting less than 1½ inches thick. Its upper bench is said to be softer and freer from impurities than the lower. The sample was collected by C. D. Smith from the working face under a cover of about 30 feet.

Sample No. 22, laboratory No. 3407, represents the coal from a mine in sec. 23, T. 9 N., R. 24 W., near Spadra. The coal is mined from a shaft 100 feet deep, and is known locally as the Spadra bed. It is in the Hartshorne horizon and is equivalent to the coal mined at Jenny Lind and Huntington, Ark., and at Hartshorne, Ind. T. The sample was taken by R. D. Mesler from one of the working faces, where the coal is 3 feet 5 inches thick with a 2-inch shale parting near the center.

Sample No. 23, laboratory No. 3503, represents the upper part of the coal bed at a mine in sec. 21, T. 3 N., R. 32 W., south of Poteau Mountain. This bed is divided into four benches, the upper three each about 2 feet thick, separated by 2-inch shale partings. The lower bench is about 4 feet thick and is separated from the upper ones by 30 inches of shale and bone. Only the lower bench is mined. This sample represents the three upper benches of the mine, including the partings, and was obtained by boring a hole upward from the roof of the lower bench through the upper three benches, the cuttings from the auger being taken as a sample. The sample was collected by C. D. Smith.

Sample No. 24, laboratory No. 3505, represents the coal produced at a mine in sec. 21, T. 3 N., R. 32 W., near Bates. This is a new mine opened by a slope from which no entries have been turned. Only the lower bench, 4 feet thick, is mined. The sample was taken by C. D. Smith from the working face and represents unweathered coal.

Sample No. 25, laboratory No. 3500, represents the coal at a mine in sec. 14, T. 4 N., R. 32 W., about 2 miles east of Hartford. The coal bed is 52 inches thick, with a 10-inch clay parting near the bottom, and the lower bench is not mined. Only the upper bench, 3 feet 6 inches thick, is represented by the sample, which was collected by C. D. Smith from one of the working faces.

Sample No. 26, laboratory No. 3497, represents the coal mined in sec. 21, T. 6 N., R. 32 W. The mine is a new one and has been in operation for only a few months. It is opened by a slope with an incline of about 15° from the outcrop. The bed is 3 feet 8 inches thick and is without parting. It has a sandstone floor and about 4 inches of draw slate between the coal and the solid shale roof. The sample was collected by C. D. Smith from one of the working faces.

CHEMICAL ANALYSES.

Analyses and other tests of the samples described above were made under uniform conditions at the fuel-testing plant. All of the samples were tested by proximate analyses. After they had been pulverized most of the samples were exposed to dry air at ordinary temperatures until their weight became stable and their basis of moisture on air drying was carefully determined. In this way the samples were brought to a nearly uniform condition as regards moisture before analysis. In the following tables the analyses of the samples as received and after air drying are given. Owing to the provisions of the law authorizing the work done at the fuel-testing plant, the names of the operators from whose mines the samples were obtained can not be printed.

For comparison of coals from the various districts the analyses of the air-dried samples are preferable. It will be seen from these analyses that the moisture retained in the Arkansas coals after air-drying is nearly constant, the limits of variation being from 0.51 to 1.28 per cent. All the samples, except five, noted in the table, were mine samples.

Analyses of coal samples from Arkansas.

[U. S. Geol. Survey fuel-testing plant, analyst.]

District	Bates-Coaldale.		Greenwood-Huntington.					
Nearest town	Bates.		Hartford.			Huntington.		
Name of sample	U. S. G. S. No. 23.	U. S. G. S. No. 24.	U. S. G. S. No. 25.	Special.	Special.	Ark. No. 1 A.	Ark. No. 1 B.	Ark. No. 1 C.[a]
Laboratory number	3503.	3505.	3500.	1066.	1068.	1046.	1045.	1114.
Analysis of sample as received:								
Prox. Moisture	6.85	3.39	4.12	.80	.90	.75	1.02	3.24
Prox. Volatile matter	25.75	24.44	18.15	17.80	18.35	18.50	17.88	17.46
Prox. Fixed carbon	43.40	66.40	69.97	72.71	71.65	73.77	73.61	66.69
Prox. Ash	24.00	5.79	7.76	8.69	9.10	6.98	7.49	12.61
Ult. Sulphur	2.32	.87	.98	1.95	1.74	1.15	1.10	1.24
Ult. Hydrogen	......	......	......	......	......	......	......	4.15
Ult. Carbon	......	......	......	......	......	......	......	74.09
Ult. Nitrogen	......	......	......	......	......	......	......	1.44
Ult. Oxygen	......	......	......	......	......	......	......	6.47
Calorific value determined:								
Calories	......	......	......	7,934	......	......	8,019	7,294
British thermal units	......	......	......	14,282	......	......	14,434	13,129
Loss of moisture on air drying	5.90	2.50	3.40	......	......	......	......	2.10
Analysis of air-dried sample:								
Prox. Moisture	1.02	.89	.75	......	......	......	......	1.17
Prox. Volatile matter	27.38	25.07	18.79	......	......	......	......	17.83
Prox. Fixed carbon	46.12	68.10	72.43	......	......	......	......	68.12
Prox. Ash	25.51	5.94	8.03	......	......	......	......	12.88
Ult. Sulphur	2.46	.89	1.01	......	......	......	......	1.27
Ult. Hydrogen	......	......	......	......	......	......	......	4.00
Ult. Carbon	......	......	......	......	......	......	......	75.68
Ult. Nitrogen	......	......	......	......	......	......	......	1.47
Ult. Oxygen	......	......	......	......	......	......	......	4.70
Calorific value determined:								
Calories	......	......	......	......	......	......	......	7,450
British thermal units	......	......	......	......	......	......	......	13,410
Fuel ratio	1.69	2.72	3.86	4.08	3.91	3.99	4.12	3.82

District	Greenwood-Huntington—Continued.						
Nearest town	Burma.					Midland.	
Name of sample	U. S. G. S. No. 2.	U. S. G. S. No. 7.	U. S. G. S. No. 3.	U. S. G. S. No. 1.	U. S. G. S. No. 6.	Special.	Special.
Laboratory number	3154.	3148.	3158.	3155.	3156.	1052.	1054.
Analysis of sample as received:							
Prox. Moisture	2.44	4.53	2.65	3.54	2.80	.79	1.00
Prox. Volatile matter	16.85	16.52	15.70	14.89	15.93	19.68	16.90
Prox. Fixed carbon	74.97	74.03	74.52	74.88	74.06	69.62	71.80
Prox. Ash	5.73	4.92	7.13	6.69	7.21	9.73	10.30
Ult. Sulphur	2.57	1.76	2.86	1.21	.73	1.11	.60
Ult. Hydrogen	......	......	......	......	......	......	......
Ult. Carbon	......	......	......	......	......	......	......
Ult. Nitrogen	......	......	......	......	......	......	......
Ult. Oxygen	......	......	......	......	......	......	......
Calorific value determined:							
Calories	......	......	......	......	......	7,790	......
British thermal units	......	......	......	......	......	14,022	......
Loss of moisture on air drying	1.60	3.70	1.90	2.70	2.00	......	......
Analysis of air-dried sample:							
Prox. Moisture	.85	.86	.76	.86	.82	......	......
Prox. Volatile matter	17.12	17.16	16.01	15.30	16.28	......	......
Prox. Fixed carbon	76.11	76.87	75.95	76.93	75.57	......	......
Prox. Ash	5.82	5.10	7.26	6.88	7.36	......	......
Ult. Sulphur	2.61	1.82	2.92	1.24	.74	......	......
Ult. Hydrogen	......	......	......	......	......	......	......
Ult. Carbon	......	......	......	......	......	......	......
Ult. Nitrogen	......	......	......	......	......	......	......
Ult. Oxygen	......	......	......	......	......	......	......
Fuel ratio	4.45	4.48	4.75	5.05	4.67	3.53	4.24

[a] Car sample.

Analyses of coal samples from Arkansas—Continued.

		Greenwood-Huntington—Continued.					
District							
Nearest town		Montreal.		Hackett.		Greenwood.	
Name of sample		U. S. G. S. No. 5.	U. S. G. S. No. 4.	U. S. G. S. No. 26.	U. S. G. S. No. 8.	U. S. G. S. No. 11.	U. S. G. S. No. 12.
Laboratory number		3152.	3150.	3497.	3157.	3173.	3175.
Analysis of sample as received:							
Prox.	Moisture	2.57	3.01	3.55	3.64	2.31	2.26
	Volatile matter	15.48	15.75	17.16	16.57	14.48	15.79
	Fixed carbon	76.17	75.93	75.46	76.00	72.66	71.91
	Ash	5.78	5.31	3.83	3.79	9.29	10.04
Ult.	Sulphur	2.05	.93	.96	.83	3.12	1.20
	Hydrogen					3.75	
	Carbon					78.37	
	Nitrogen					1.52	
	Oxygen					3.95	
Calorific value determined:							
	Calories					7,549	
	British thermal units					13,588	
Loss of moisture on air drying		1.80	2.20	2.80	3.00	2.40	1.60
Analysis of air-dried sample:							
Prox.	Moisture	.78	.83	.77	.66	.77	.67
	Volatile matter	15.76	16.21	17.65	17.03	15.21	16.05
	Fixed carbon	77.33	78.36	77.63	78.35	74.45	73.07
	Ash	5.88	5.43	3.94	3.96	9.52	10.20
Ult.	Sulphur	2.09	.95	.99	.85	3.20	1.22
	Hydrogen					3.84	
	Carbon					80.30	
	Nitrogen					1.56	
	Oxygen					4.05	
Calorific value determined:							
	Calories					7,735	
	British thermal units					13,923	
Fuel ratio		4.92	4.78	4.40	4.54	4.90	4.55

		Bonanza-Jenny Lind.							
District									
Nearest town		Bonanza.			Jenny Lind.				
Name of sample		Ark. No. 2 A.	Ark. No. 2 B.	Ark. No. 2 C.[a]	Ark. No. 3 A.	Ark. No. 3 B.	Ark. No. 3 C.[a]	U. S. G. S. No. 10.	Ark. No. 6.[b]
Laboratory number		1053.	1049.	1160.	1115.	1118.	1296.	3151.	1542.
Analysis of sample as received:									
Prox.	Moisture	.78	.95	2.23	1.60	1.63	2.19	1.95	3.80
	Volatile matter	16.60	18.70	16.03	17.40	16.86	19.47	15.55	13.89
	Fixed carbon	73.53	73.38	72.55	73.09	69.03	66.71	73.27	68.50
	Ash	9.09	6.97	9.20	7.91	12.66	11.63	9.23	13.81
Ult.	Sulphur	2.50	2.12	1.78	1.42	1.46	1.28	1.23	1.26
	Hydrogen			4.24			4.17		
	Carbon			78.83			75.31		
	Nitrogen			1.38			1.53		
	Oxygen			4.48			6.08		
Calorific value determined:									
	Calories		7,993	7,639	7,868		7,480		
	British thermal units		14,387	13,750	14,162		13,464		
Loss of moisture on air drying				1.50	.80	.80	1.40	1.20	3.00
Analysis of air-dried sample:									
Prox.	Moisture			.74	.81	.84	.80	.76	.82
	Volatile matter			16.26	11.54	16.81	14.75	15.74	14.32
	Fixed carbon			73.66	73.68	69.59	67.65	74.16	70.62
	Ash			9.39	7.97	12.76	11.80	9.34	14.24
Ult.	Sulphur			1.90	1.51	1.47	1.30	1.25	1.30
	Hydrogen			4.13			4.07		
	Carbon			80.03			76.37		
	Nitrogen			1.40			1.55		
	Oxygen			3.20			4.91		
Calorific value determined:									
	Calories			7,756	7,931		7,586		
	British thermal units			13,961	14,275		13,655		
Fuel ratio		4.43	3.92	4.52	4.20	4.10	3.43	4.71	4.93

[a] Car sample.

[b] Slack car sample.

Analyses of coal samples from Arkansas—Continued.

District	Bonanza-Jenny Lind—Continued.				Charleston.	Paris.
Nearest town	Jenny Lind.			Fort Smith.	Auburn.	Paris.
Name of sample	Special.	Special.	U. S. G. S. No. 9.	U. S. G. S. No. 21.	U. S. G. S. No. 13.	U. S. G. S. No. 14.
Laboratory number	1030.	1031.	3153.	3372.	3218.	3174.
Analysis of sample as received:						
Prox. Moisture	.95	.80	3.18	2.19	3.80	2.77
Volatile matter	17.91	17.20	14.64	14.00	15.96	14.69
Fixed carbon	71.52	74.35	76.06	72.15	75.86	73.47
Ash	9.62	7.65	6.12	11.66	4.38	9.07
Ult. Sulphur	2.07	1.64	1.51	2.06	2.21	2.79
Hydrogen						4.02
Carbon						78.71
Nitrogen						1.46
Oxygen						3.95
Calorific value determined:						
Calories	7,831					7,652
British thermal units	14,096					13,774
Loss of moisture on air drying			2.40	1.40	2.60	2.20
Analysis of air-dried sample:						
Prox. Moisture			.79	.80	1.23	.58
Volatile matter			15.00	14.20	16.30	15.02
Fixed carbon			77.93	73.18	77.88	75.12
Ash			6.27	11.83	4.49	9.27
Ult. Sulphur			1.55	3.09	2.27	3.04
Hydrogen						3.87
Carbon						80.48
Nitrogen						1.49
Oxygen						2.04
Calorific value determined:						
Calories						7,824
British thermal units						14,084
Fuel ratio	3.98	4.32	5.20	5.15	4.75	5.00

District	Denning-Coal Hill.						
Nearest town	Denning.		Altus.	Coal Hill.			
Name of sample	Special.	Special.	U. S. G. S. No. 20.	U. S. G. S. No. 19.	Ark. No. 5 A.	Ark. No. 5 B.	Ark. No. 5 C.[a]
Laboratory number	1040.	1042.	3371.	3370.	1130.	1131.	1331.
Analysis of sample as received:							
Prox. Moisture	.85	.84	3.77	3.41	1.38	1.80	2.36
Volatile matter	14.45	16.46	13.96	12.09	14.76	15.00	12.68
Fixed carbon	76.41	75.32	79.35	78.42	76.91	75.94	72.88
Ash	8.29	7.38	2.92	6.08	6.95	7.26	12.08
Ult. Sulphur	2.05	1.91	.74	4.05	1.52	1.94	1.99
Hydrogen							3.82
Carbon							76.44
Nitrogen							1.37
Oxygen							4.30
Calorific value determined:							
Calories		8,136			7,961		7,366
British thermal units		14,645			14,330		13,259
Loss of moisture on air drying			2.80	2.40	.70	1.30	1.10
Analysis of air-dried sample:							
Prox. Moisture			1.00	1.03	.68	.51	1.28
Volatile matter			14.36	12.39	14.87	15.19	12.82
Fixed carbon			81.64	80.35	77.45	76.94	73.69
Ash			3.00	6.23	7.00	7.36	12.21
Ult. Sulphur			.76	4.15	1.53	1.97	2.01
Hydrogen							3.74
Carbon							77.29
Nitrogen							1.39
Oxygen							3.36
Calorific value determined:							
Calories					8,017		7,448
British thermal units					14,431		13,406
Fuel ratio	5.29	4.58	5.68	6.48	5.21	5.06	5.74

[a] Car sample.

Analyses of coal samples from Arkansas—Continued.

District	Spadra.			Russellville.	
Nearest town	Spadra.		Clarksville.	Russellville.	
Name of sample	U. S. G. S. No. 17.	U. S. G. S. No. 22.	U. S. G. S. No. 18.	U. S. G. S. No. 15.	U. S. G. S. No. 16.
Laboratory number	3368.	3407.	3369.	3177.	3176.
Analysis of sample as received:					
Prox. Moisture	2.11	2.15	1.72	2.33	2.07
Prox. Volatile matter	11.42	10.82	10.46	10.60	9.81
Prox. Fixed carbon	77.83	76.87	79.50	77.67	78.82
Prox. Ash	8.64	10.16	8.32	9.40	9.30
Ult. Sulphur	1.99	2.30	2.49	1.81	1.74
Ult. Hydrogen	....	....	....	....	3.62
Ult. Carbon	....	....	....	....	80.28
Ult. Nitrogen	....	....	....	....	1.47
Ult. Oxygen	....	....	....	....	3.59
Calorific value determined:					
Calories	7,619	....	7,704	....	7,612
British thermal units	13,714	....	13,867	....	13,703
Loss of moisture on air drying	1.00	1.40	.70	1.60	1.40
Analysis of air-dried sample:					
Prox. Moisture	1.12	.76	1.03	.74	.68
Prox. Volatile matter	11.54	10.97	10.53	10.77	9.93
Prox. Fixed carbon	78.62	77.96	80.06	78.93	79.94
Prox. Ash	8.73	10.30	8.38	9.55	9.43
Ult. Sulphur	2.01	2.33	2.51	1.84	1.76
Ult. Hydrogen	....	....	....	....	3.67
Ult. Carbon	....	....	....	....	81.42
Ult. Nitrogen	....	....	....	....	1.49
Ult. Oxygen	....	....	....	....	3.64
Calorific value determined:					
Calories	7,693	....	7,758	....	7,720
British thermal uuits	13,853	....	13,965	....	13,896
Fuel ratio	6.82	7.11	7.59	7.33	8.04

COKING TESTS.

Although some of the Arkansas coals, especially those from the western part of the field, seem to coke in laboratory experiments, none of them have yet been successfully coked on a commercial scale. Laboratory tests made at St. Louis indicated that the samples called Arkansas Nos. 1 and 2, representing the mines at Huntington and Bonanza, respectively, are coking coals.[a] Parts of each of the five representative carload samples sent to the fuel-testing plant were tried in a beehive coking oven and all gave negative results.[b]

In order to determine whether or not the Arkansas coals could be made to produce coke by mixing them with small amounts of more highly bituminous coal from other sources, or by adding pitch to act as a binder, a test was made of lump and slack coal from mine No. 18 at Jenny Lind. A charge consisting of a small amount of briquets, containing 6 per cent of hard pitch, was placed in an oven with a coking coal and produced a dense coke high in ash.

Equal parts of unwashed slack mixed with 8 per cent of hard pitch and briquets made of the same material gave a very dark coke with large cells. This charge contained 640 pounds of pitch and weighed

---

[a] Prof. Paper U. S. Geol. Survey. No. 48, pt. 1, 1904, p. 300.

[b] Idem, pt. 3, pp. 1328-1332.

8,000 pounds. It burned 42 hours and yielded 4,056 pounds of coke and 539 pounds of breeze and ash.

Slack mixed with 8 per cent of pitch, without briquetting, gave a dark-gray coke that was high in ash and had no metallic ring, which can be used where high ash and sulphur are not important considerations. These tests are valuable, since they show that although most of the Arkansas coals are naturally noncoking they may be made so by the addition of pitch.

BRIQUETTING TESTS.

The friable nature of the coal and the high percentage of slack resulting from it are notable drawbacks connected with the coal-mining industry in Arkansas. The slack has a high fuel value and is not notably impure as regards ash, but is difficult to burn economically, since it requires special grates and is not worth more than one-third as much as the lump coal. For this reason any method of utilizing the slack and increasing its value is of considerable importance, and the possibility of making it into briquets has therefore been considered. The fuel-testing plant at St. Louis was equipped with two briquetting machines, one of English make, producing a rectangular briquet 6 by 5 by 4 inches, the other of American design, producing eggettes weighing 0.3 pound. Slacks from nearly every part of the Arkansas field were tested, but all attempts to produce briquets from the coal alone were unsuccessful. It was found, however, that by adding to the slack from 6 to 10 per cent of pitch, obtained from the by-products of various gas plants, good briquets, that have a somewhat higher heat- and steam-producing value than the original coal, can be made. A full description of the various briquetting tests made at St. Louis is contained in the report of the fuel-testing plant, pp. 1389 to 1472, from which the following more salient results have been abstracted.[a]

Slack from the mines at Huntington was tested with a hard pitch, 6 tons being mixed with 9.25 per cent of pitch and made into briquets in the English machine. The briquets were compact and well pressed, but were too friable for handling, showing that they contained insufficient pitch. They were also brownish in color and very dirty. Coal from Jenny Lind was also tested with hard pitch, briquets being made in the English machine. Six tons of crushed lump coal were run through the machine, which was set to give approximately 11 per cent of pitch, but the briquets were pitchy and wrinkled, and probably contained nearer 15 than 11 per cent. Although these were not commercial briquets, a boiler test made with them showed that they were well adapted to produce steam. The pitch used for both these lots of briquets was too hard to give the best results.

---

[a] Report of the operations of the coal-testing plant, 1904; Prof. Paper U. S. Geol. Survey No. 48, pt. 3, 1906, pp. 1389-1472.

Seventeen tons of coal from the Denning field were briquetted in the English machine with 6 per cent of comparatively soft pitch, for the purpose of making locomotive tests on the Missouri Pacific Railway. Excellent briquets were obtained, which were readily handled while warm, stood a good deal of handling when cold, and did not break so readily as the original lumps of coal. They were tested for locomotive use in comparison with Illinois coal. Three trips were made from St. Louis to Washington, Mo., and return, making a total of 324 miles for each fuel. The comparative results of the test are best stated in terms of the number of miles run per ton of coal, which for the Arkansas briquets averaged 21 miles per ton, while with the coal from Illinois only 19 miles per ton was made by the same train. The results showed that the Arkansas briquets have greater efficiency than the Illinois coal and indicate that by briquetting the slack it is possible to obtain a high-grade fuel. The briquets were said to be too large for locomotive use and had to be broken before the engine could steam well.

BOILER TESTS.

Seventy boiler tests of car samples representing coals from many different localities and fields in the United States were made under uniform conditions at the fuel-testing plant in St. Louis, and the tabulated results obtained have been published in part 2 of the report of the coal-testing plant for the year 1904.[a] Eight of these tests were of coals from the Arkansas field, including both natural coal and briquets made by combining slack or crushed coal with a certain amount of pitch. Four of the tests were of natural coal.

The boiler plant was equipped with two 210-horsepower Heine water-tube boilers. The same boilers were used for all the tests, and an effort was made to have the coals nearly uniform in size, the usual size being small lump and egg mixed with varying amounts of slack. Full details regarding these tests are available for further examination in the professional paper cited, from which a few of the more obvious and important results have been abstracted in the accompanying table to show the relative efficiencies of various Arkansas coals. From these figures it will be seen that while the coal (Arkansas No. 5) from the Denning district is higher in the scale of classification than the other coals tested, its efficiency in heat and steam production is somewhat lower. The results selected from the report cited for purposes of comparison are—

---

[a] Prof. Paper U. S. Geol. Survey No. 48, 1906.

1. The number of pounds of water at the boiling point which can be converted into steam at the same temperature by the combustion of 1 pound of dry coal.

2. The amount of heat absorbed by the boiler, stated in British thermal units. This is equal to the number of pounds of water evaporated at 212° multiplied by 965.7 the number of British thermal units required to convert 1 pound of water into steam. This result is given for comparison with the next to indicate the proportion of the total heat value of the coal available for the production of steam. It is a factor which depends to a considerable extent on the appliances for burning the coal, and with engines better adapted to any particular coal would probably be larger than the figures given.

3. The calorific value of the dry coal stated in British thermal units as determined by the oxygen calorimeter. This factor gives the total heat value of the coal.

4. The number of pounds of coal per hour required to produce one indicated horsepower. This figure is calculated theoretically from the determinations given in the first column, together with other factors, it being estimated that 34½ pounds of water evaporated per hour into dry steam from and at 212° F. equal 1 horsepower.

5. The last column gives the number of pounds of dry coal consumed per hour per electric horsepower, which may be regarded as the actual measured horsepower produced. It will be seen that as far as these tests go the coals from Bonanza and Jenny Lind, Arkansas Nos. 2 and 3, are more efficient than those from Denning and Huntington, Arkansas Nos. 5 and 1, respectively. In order to compare the efficiency of the Arkansas coals in general with the coals from other parts of the United States with which they come in competition, a second table is given in which the average results from 4 Arkansas coals are combined with similar results from 12 coals from West Virginia, 6 from Illinois, 4 from Indian Territory, 8 from Kansas, and 8 from Missouri. It will be readily seen from this table that average Arkansas coals are nearly, though probably not quite, as efficient as those from West Virginia, and that they are better than coals from Indian Territory and Kansas, and very much better than those from Illinois and Missouri.

Although these results and the comparisons based on them would undoubtedly be modified if they were obtained from boilers and grates especially adapted to the coal burned, it is believed that they show fairly well the relative efficiency of the Arkansas coal as compared with other coals with which it comes into competition.

Determinations of efficiency of four Arkansas coals by boiler tests, and averages of coals from various other States for comparison.

Designation.	Water at 212° F. evaporated per pound of coal.	British thermal units absorbed by boiler.	Calorific value in B.t.u. determined by oxygen calorimeter.	Pounds of coal per hour per indicated horsepower.	Pounds of coal used per electric horsepower hour
	Pounds.				
Arkansas No. 1, Huntington	8.86	8,556	13,572	3.12	3.86
Arkansas No. 2, Bonanza	9.72	9,387	14,244	2.91	3.59
Arkansas No. 3, Jenny Lind	9.50	9,174	14,151	2.98	3.68
Arkansas No. 5, Coal Hill	8.04	7,764	13,617	3.52	4.34
4 Arkansas coals	9.03	8,720	13,893	3.13	3.87
12 West Virginia coals	9.72	9,388	14,466	2.92	3.61
6 Illinois coals	7.55	7,292	12,292	3.75	4.64
4 Indian Territory coals	8.19	7,909	12,820	3.46	4.28
8 Kansas coals	8.23	7,948	12,983	3.20	4.26
8 Missouri coals	7.60	7,239	12,169	3.77	4.66
2 Alabama coals	8.17	7,894	12,746	3.33	4.11

CONDITIONS OF MINING AND DEVELOPMENT.

PRODUCTION.

The statistics of coal mining in Arkansas for the last sixty-five years show a production of 220 tons in the year 1840 and 200 tons in 1860.[a] During those years the coal was used almost exclusively for blacksmithing, and was obtained from strip pits, which were worked only occasionally. The development of the coal industry on a commercial scale was started about 1870, when a steam plant was put in operation at the mouth of Spadra Creek. Coals from the Ouita basin and the Coal Hill mines were brought to market about 1873, after the extension of the Little Rock and Fort Smith Railroad.

By the year 1880 the production had reached 14,778 tons, and from that time it steadily increased until 1903, when it attained a maximum of 2,229,172 tons. The decline in production since 1903 is attributed to the competition of fuel oil, of which there was overproduction in Texas. Present conditions, however, indicate that the demand for Arkansas coal is again increasing, and were it not for the scarcity of labor and a general strike from April to June, inclusive, the production in 1906 would probably have nearly equaled that of 1903.

The four tables following, abstracted from Mineral Resources of the United States for 1905,[b] show the progressive increase of the coal production since 1840, the amounts produced in the various counties since 1901, and the production, value, average price per ton, and number of men employed in the various counties in 1904 and 1905.

From the third table it will be seen that the greatest output is from Sebastian County, though the coals of the eastern end of the district—namely, from Shinn and Ouita basins—command the highest price, while those from the Paris basin are second in price and those from the Spadra and Coal Hill fields third. A fourth table showing the average price per ton of the coals of neighboring States which come in competition with the Arkansas coals is given for comparison.[a]

---

[a] Ann. Rept. Geol. Survey Arkansas for 1888, vol. 3, p. 27.

[b] Mineral Resources U. S. for 1905, U. S. Geol. Survey, 1906, pp. 550-552.

Average production of coal in Arkansas, 1840–1905.

[Short tons.]

Year.	Quantity.	Year.	Quantity.	Year.	Quantity.
1840	230	1888	276,871	1898	1,205,479
1860	200	1889	279,584	1899	843,554
1880	14,778	1890	399,888	1900	1,447,945
1881	20,000	1891	542,379	1901	1,816,136
1882	25,000	1892	535,558	1902	1,943,932
1883	50,000	1893	574,763	1903	2,229,172
1884	75,000	1894	512,626	1904	2,009,451
1885	100,000	1895	598,322	1905	1,934,673
1886	125,000	1896	675,374		
1887	129,600	1897	856,190		

Coal production of Arkansas, 1901–1905, by counties.

[Short tons.]

County.	1901.	1902.	1903.	1904.	1905.	Increase (+) or decrease (−), 1905.
Franklin	504,946	338,013	394,884	408,494	420,384	+ 11,890
Johnson		193,258	198,999	217,667	214,234	− 3,433
Logan		21,751	27,286	35,300	26,090	− 9,210
Pope		34,966	48,836	51,488	39,685	− 11,803
Sebastian	1,305,190	1,325,181	1,528,888	1,234,794	1,189,455	− 45,339
Other counties and small mines	6,000	30,763	[a]30,279	61,708	44,825	− 16,883
Total	1,816,136	1,943,932	2,229,172	2,009,451	1,934,673	− 74,778
Total value	$2,068,613	$2,539,214	$3,360,831	$3,102,660	$2,880,738	−$221,922

[a] Includes also production of Perry County.

Coal production of Arkansas, in 1904 and 1905, by counties, uses, etc.

1904.

County.	Loaded at mines for shipment.	Sold to local trade and used by employees.	Used at mines for steam and heat.	Total quantity.	Total value.	Average price per ton.	Average number of days active.	Average number of employees.
	Short tons.	*Short tons.*	*Short tons.*	*Short tons.*				
Franklin	400,994	2,000	5,500	408,494	$582,703	$1.43	168	695
Johnson	210,062	2,050	5,555	217,667	392,445	1.80	175	652
Logan	30,700	3,770	830	35,300	77,461	2.19	194	115
Pope	44,053	460	6,975	51,488	168,245	3.27	189	229
Sebastian	1,174,630	24,544	35,620	1,234,794	1,780,203	1.44	158	2,820
Scott and Washington	59,720	1,068	920	61,708	101,603	1.65	194	69
Total	1,920,159	33,892	55,400	2,009,451	3,102,660	1.54	165	4,580

1905.

County.	Loaded at mines for shipment.	Sold to local trade and used by employees.	Used at mines for steam and heat.	Total quantity.	Total value.	Average price per ton.	Average number of days active.	Average number of employees.
Franklin	413,384	1,000	6,000	420,384	$585,419	$1.39	202	750
Johnson	204,091	1,771	8,372	214,234	364,390	1.70	164	730
Logan	24,390	800	900	26,090	58,388	2.24	191	104
Pope	33,952	813	4,920	39,685	140,030	3.53	217	140
Sebastian	1,150,856	7,667	30,932	1,189,455	1,668,597	1.40	168	2,389
Scott and Washington	42,500	1,245	1,080	44,825	63,914	1.43	216	79
Total	1,869,173	13,296	52,204	1,934,673	2,880,738	1.49	177	4,192

---

[a] Op. cit., p. 504.

Average prices for coal at the mines in Arkansas and neighboring regions, 1901-1905.

[Per short ton.]

State or Territory.	1901.	1902.	1903.	1904.	1905.
Alabama	$1.10	$1.20	$1.22	$1.20	$1.21
Arkansas	1.14	1.31	1.51	1.54	1.49
Illinois	1.03	1.03	1.17	1.10	1.06
Indiana	1.01	1.10	1.23	1.11	1.05
Indian Territory	1.62	1.51	1.82	1.82	1.76
Iowa	1.39	1.47	1.65	1.61	1.56
Kansas	1.22	1.30	1.52	1.52	1.46
Kentucky	.95	.99	1.06	1.04	.99
Missouri	1.24	1.38	1.61	1.63	1.58

METHODS OF MINING.

The methods of mining practiced in Arkansas are well adapted to the local conditions. The following general statements regarding these methods are given for the information of readers who are not familiar with those conditions.

System of working coal.—Coal was first mined in Arkansas by stripping, and in some pits this method of mining is still followed, but most of the coal now mined is from deeper workings, which are reached either by slopes or shafts, the deepest mine in the State being a 480-foot shaft in Shinn basin in the eastern part of the field. In regard to mining by stripping little need be said, since the workings operated in this way are of rather small extent, and much of the coal accessible by this method has already been mined. As a rule, the overlying soil and shale are removed either by hand or by horsepower to a maximum depth of about 10 feet. The quality of the coal obtained is not greatly affected by weathering, and some coal beds that are only 18 inches thick can be profitably worked.

Most of the deeper mines are still comparatively shallow, the average depth being less than 200 feet. In such mines, whether opened by shaft or slope, the room-and-pillar system of mining prevails, with local modifications, throughout the whole field. The pillars are not drawn after the rooms are exhausted. The entries are usually double in the larger mines, but in many small mines single entries are used. Some of the beds, especially those in which the coal is thin but of high grade, could probably be worked more economically by the "long wall" system, though it is not known that this has been employed anywhere up to the present time.

Mining.—The actual mining of the coal is generally done by shooting or blasting it off the solid face of the bed. Owing to the friable nature of the coal, this practice results in the formation of a large percentage of slack, but it seems to be the most effective method possible in many of the mines, where the floor is hard and not well adapted to undercutting. In some of the smaller mines, where the coal is of high grade and commands a good price, undercutting by hand is the method used, and in a few mines where the bed is divided by a parting of soft shale or clay this is mined out by hand and the upper bench wedged down, after which the lower one is either wedged up or shot off the solid. Where the coal is hand-mined the percentage of slack is generally lower regardless of other characters of the coal.

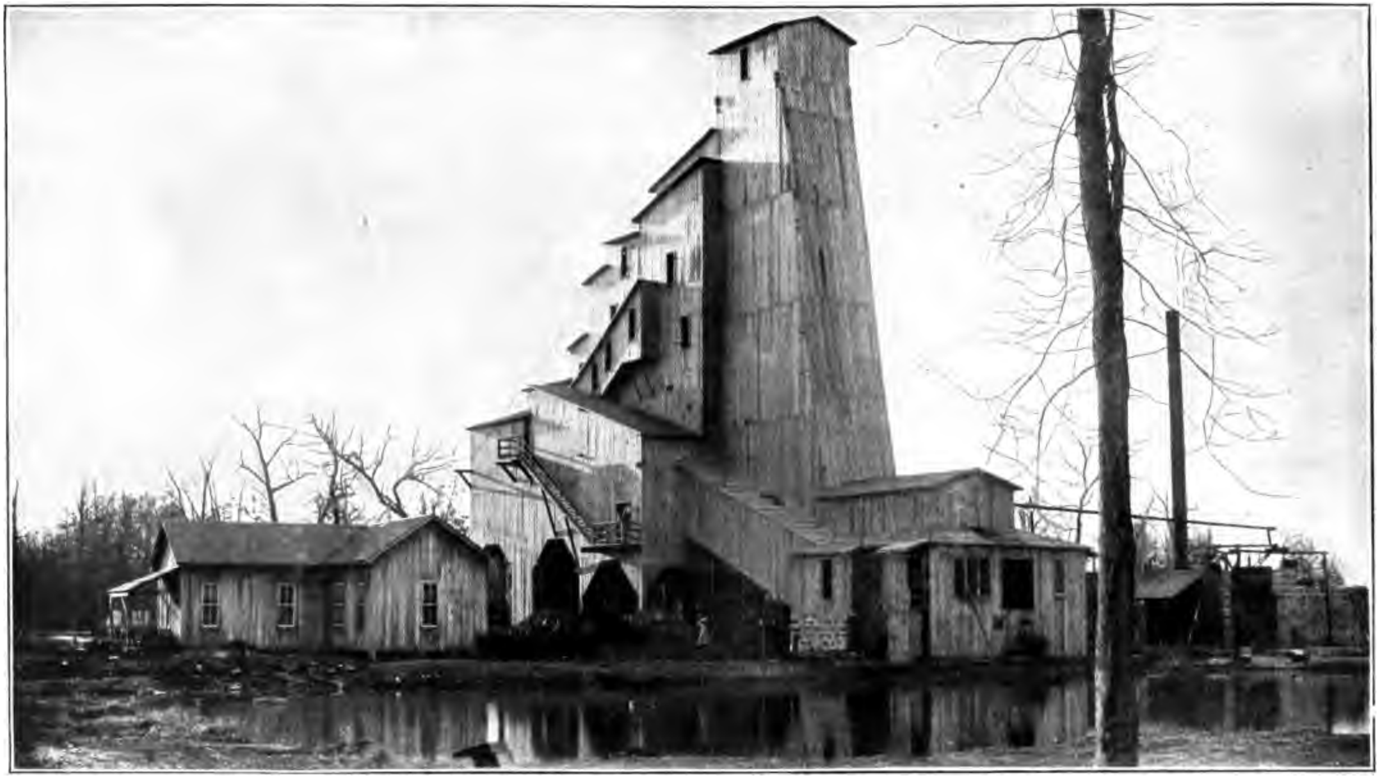
No mining machines of any kind are used in Arkansas, and such machines are not likely to be used in the immediate future, since the beds generally are comparatively thin, and the percentage of slack from the cuttings of machines would probably be nearly as great as that made by shooting from the solid.

Haulage, ventilation, and drainage.—In most of the larger mines haulage from the rooms to the main heading is by mules and in the main gangway by rope or cable, or, as in one of the mines at Bonanza, by electric motors. In many of the mines mules are used throughout and in a few instances the cars are moved wholly by hand. Ventilation is accomplished in the larger mines by fans and in the smaller ones by fire boxes. The mines are comparatively free from gas, and accidents from this cause are relatively rare. During the year ending June 30, 1906, 8 men were killed and 34 injured, among over 4,000 employed in the mines, and most of these accidents were due to other causes than gas. Open lamps are used throughout practically all the workings. Since most of the entries are below drainage levels, pumping is almost invariably necessary. In most of the mines steam pumps are used, but some of the small mines are bailed with buckets.

Minimum limit of thickness.—The minimum thickness of coal mined for shipment is found in the Ouita basin, where the bed averages less than 2½ feet. That mined at Paris is between 2 and 2½ feet, and the coal mined for local supply in the Philpott basin is between 18 and 20 inches thick. Special agreements are made with the miners in working these thin coals. In general a uniform rate per ton applies throughout the Arkansas field for mining all coals in beds more than 2 feet 10 inches thick. Mining in thinner beds is considered "deficient work," for which special rates are made. Under favorable conditions it is probable that beds only 18 inches thick will ultimately be worked at a profit.

PREPARATION OF THE COAL FOR MARKET.

The coal is sold either in the form it comes from the mines, as "mine-run," which includes both lump and slack, or, more commonly, is prepared for sale by passing it over screens which separate the slack from the lump. In general, bar screens not more than 6 feet wide and 16 feet long, with 1⅛ inch spaces between the bars, are used. At some of the mines lump coal to be used for domestic purposes is graded into various sizes, such as pea, nut, and egg. In the Paris basin all of the lump coal is separated from the slack by hand with a fork, and the slack left in the gob. The same method prevails in the Ouita basin and at many of the small mines which supply local mar-



BREAKER AT SCRANTON ANTHRACITE COAL COMPANY'S MINE. SPADRA DISTRICT.

Showing a new and modern equipment for hoisting, screening and sorting the Arkansas anthracite coal.

kets within the coal field. The slack from all of the larger mines is marketed, the prices being usually less than one-third the price of lump coal. Slack from the bituminous coals of the west end of the field is sold in Kansas City and St. Louis, where it is used for producing steam in stationary engines. The semianthracite slack from the Spadra field is used in lead and zinc smelters at Joplin, Mo. One of the most complete plants for screening and sorting coal in Arkansas is shown in Pl. V.

Within the last two years the Central Coal and Coke Company has established a plant near Hackett for washing slack produced at their mines. Many of the impurities are thus removed from the slack, together with the finer coal dust, and the remainder, about 80 per cent of the original quantity, is raised in value almost to that of the lump coal. Washing plants have not yet been established in other parts of the field, though it is probable that similar results can be obtained elsewhere.

LABOR.

Except in a few very small mines all of the labor of extracting the coal is performed under contract by piecework at a definite rate per ton. The operator, therefore, has little to do in directing the miners except to decide what parts of the land shall be first developed. The rates for mining coal are established by definite agreements between the operators and the labor union. There are practically no miners in the field except union men. The conditions of mining as affected by the labor element, therefore, are best set forth by the contract between the operators and the labor union, which is given below.

During 1904 and 1905 the coal-mining industry in Arkansas was not interrupted by the labor strikes which prevailed in other States, but in 1906 all of the principal mines were shut down from the 1st of April to the 1st of July. Only a few small mines and strip pits worked by nonunion miners or by union men under special agreements continued in operation, and their output was unimportant. For two months preceding the strike all of the mines were unusually active, the coal obtained being hoarded in anticipation of the trouble. The amount of coal produced during these months was limited only by the capacity of the mines and the number of the men available.

PORTION OF MINERS' CONTRACT FOR DISTRICT 21, U. M. W. A.[a]

Prices for Mining in Arkansas.

All coal in Arkansas, at the option of the operator, to be mined and paid for on a sliding scale in proportion to the percentage, or weight, of lump coal contained in the whole, based on the present prices and size of screens where such are established.

That the question of establishing a scale of prices for mining mine-run coal in all the anthracite mines of Arkansas be referred to Commissioner Brown, on the part of the operators, and District President Hanraty, of District 21, on the part of the miners, for adjustment.

---

[a] Joint Interstate Agreement *and* Contracts for Districts 14, 21, and 25 of Operators and Miners, adopted at *Kansas City, Mo., June 16, 1906*, for period ending March 31, 1908, pp. 39-51.

The price for mine-run coal per ton shall be 62 cents.

For screened coal, per ton, 90 cents.

The operators are to have the option of paying on a screened-coal or mine-run basis. When the coal is mined on a screened-coal basis, the screens used shall be not more than 6 feet wide, have bars not more than 16 feet long, and a 1⅛-inch space between the bars.

OUITA.

For hand-picked coal, free from slack, slate, sulphur, bony, and black jack, the price shall be as follows:

From the 1st of September to the 1st of March	$1.22
From the first of March to the 31st of August	1.07

SPADRA.

For screened coal per ton, from the 1st of September to the 1st of March	$1.02
From the 1st of March to the 31st of August	.92

For all coal under 3 feet in height, for each 3 inches less of coal, there shall be 5 cents per ton additional to above prices.

The price for narrow work shall be as follows:

20 feet gob entries or air courses	per yard	$1.12
18 feet gob entries or air courses	do	1.25
16 feet gob entries or air courses	do	1.50
12 feet gob entries or air courses	do	1.75
8 feet entries or air courses	do	2.00
All brushing, 16 inches	do	1.12

And all over 16 inches, 7 cents for each inch extra.

The company shall have the right to do all brushing by shift work at $2.56 per day when desired.

All cross-cuts in rooms shall be	per yard	$1.12
All room turning shall be	do	1.12

RUSSELLVILLE.

Ten cents per ton less than the price paid at Ouita.

ENTRY YARDAGE, ETC.

Entry, yardage, and deficient work will be 1903 rate. The same rules and customs defining deficient work in district 21 shall be in force during the life of this agreement.

For mining hand-picked or forked coal free from slate, slack, and other impurities, $1.05 per ton shall be paid.

Where draw slate or rock comes with coal the following prices shall be adopted:

For all over 1 inch and under 5 inches, 5 cents per ton extra; over 5 inches and less than 10 inches, 9 cents per ton extra; over 10 inches and less than 15 inches, 14 cents per ton extra; over 15 inches and less than 20 inches, 19 cents per ton extra.

LOCAL CONDITIONS.

The brushing price at Bonanza, Jenny Lind, Coal Hill, and Denning shall be $1.40 for 18 inches of brushing. Where the company requires more than 18 inches to be brushed, they agree to pay 8 cents per inch for each additional inch over the 18 inches.

Draw slate in air courses will be paid as follows:

For 3 inches or over	$0.25
For 6 inches or over	.50
For 9 inches or over	.75
For 12 inches or over	1.00

All coal in Arkansas 2 feet 10 inches and less in height shall be considered deficient work, except where special price has been made.

Scale of prices to be paid for draw slate and rock at Bache & Denman's mines at Burma and Montreal No. 2:

Over 4 inches and up to 8 inches, 56 cents per yard; over 8 inches and up to 12 inches, 84 cents per yard; over 12 inches, to be settled locally. Brushing entries to be $1.41 per yard.

Where bottom is taken up in rooms and room necks it shall be paid 56 cents per yard. This applies to Bache & Denman's mines at Burma only.

All break-throughs in Arkansas, when required to cut through, to be paid at the 1903 rate.

Brushing bottom in entries, at Dallas mine, Burma, Ark.; width of brushing to be 4 feet, height 4 feet 6 inches on top of rail. All over and above this height and width to be paid at the rate of 7 cents per inch.

Air courses and rooms, 4 cents per inch for bottom brushing, width or roadway 3 feet.

Where miners at Coal Hill, No. 18 Jenny Lind, and Denning, Ark., have been pushing cars both ways the company shall assist the miner one way when necessary; and all miners in the Indian Territory who have been pushing their cars both ways shall receive for all coal pushed over 200 feet 5 cents per ton extra. The conditions that prevail at Lehigh apply to all mines on the Atoka track in regard to lowering cars down to the switch.

That the loading rate of the McCurtain machine scale be extended over those mines in Arkansas which now carry 62 cents per ton mine-run tonnage rate. Where punching machines are installed, in Arkansas, the McCurtain cutting rate to be adopted. Where chain machines are installed, in Arkansas, the rate for runners and helpers shall be established by the commissioner and district president, and in case of their failure to agree, the matter will be taken up in the manner provided for other controversies.

Inside day wage scale.

Track layers	per day	$2.56
Track layers' helpers	do	2.36
Trappers	do	1.13
Bottom cagers	do	2.56
Drivers	do	2.56
Trip riders	do	2.56
Pushers	do	2.56
Water haulers and machine haulers	do	2.56
All other inside day labor	do	2.36
Spragging, coupling, and greasing, when done by boys	do	1.75
Shot firers under normal conditions	do	3.00

The fire boss shall receive $3.04 per day and shall be subject to discharge by the management of the mine without appeal; if competent, shall be given other work.

The fire runner shall receive not less than $2.56 where such is employed.

Electric hoist operators:

For boys[a]	per day	$2.00
Electric slope engineers	do	2.56
Motormen	do	2.56
Pump men (inside)	do	2.56
Head machinist	do	3.10
Machinists	do	2.75
Day wages for digging coal	do	2.81
Machine runners	do	3.00
Machine helpers	do	2.75
Shaft sinkers	do	3.04

---

[a] "*Boys*" means those of maximum age of 19 years.

Outside day wage scale.

First blacksmiths	per day	$3.00
Second blacksmiths	do	2.75
Blacksmiths' helpers	do	2.36
Carpenters[a]	do	2.43
All other outside day labor[b]	do	2.02½

Scale for engineers.

Engineers:		
First class, 500 tons and over	per month	$79.00
Second class, 300 to 500 tons	do	73.00
Third class, 300 tons or less	do	65.00

Tail rope and slope engineers, 5.9 per cent above present wages.

The minimum rate for tail rope and slope engineers shall be $2.38 per day, or $62 per month; provided, further, that the maximum rate for tail rope and slope engineers shall be $2.70 per day or $70 per month, twenty-six days to constitute a month's work and nine hours to constitute a day's work. All overtime in excess of nine hours to be paid for at a proportionate rate per hour.

The mining prices inside and outside day-wages scale (except engineers) provided for in this contract is based upon an eight-hour work day.

GENERAL CONDITIONS.

There shall be two pay days a month and the operators shall issue to each employee a statement of his account, which the employee may retain. The dates of pay days shall be arranged between the respective companies and their employees.

Where air courses are driven in chute or platform work—that is, where the coal is in a greater pitch than 20°—the work shall be considered as air-course work and shall be paid for at the regular district price, provided such air course or brake-through is cut or sheared before being shot.

The company shall put in all batteries, wing boards, and platforms in all chute work in district No. 21.

The miners shall load their own coal in pitching veins in this district at the regular scale price.

No person employed underground shall use an inferior grade of lard oil, and the use of any other except lard oil is prohibited. Rope riders in mine slopes are excepted.

The taking up of bottom for stub switches for chute rooms will be done by the miner and payment for same is referred to local union and mine officials for adjustment. In the event of their failure to agree, general resolutions to govern.

Where coal is screened before being weighed it shall be dumped on flat sheets and passed over the screen specified in the Pittsburg agreement, and there shall be no obstruction on said screen.

When an employee leaves the employment of a company he shall receive all money due him within three days from the date of notice. Settlement must be asked for between the hours of 8 a. m. and 6 p. m. on day settlement is due.

All company men shall receive an equal share of all work when competent to do such work.

The gas man shall place marks at last inside break-through, showing clearly whether there is any standing gas in working place. Should there be standing gas, he shall place gas mark at room neck in addition to mark at inside break-through; but should working place be clear, he shall place marks so indicating this at coal face. No miner shall be permitted to brush out gas.

---

[a] *Provided*, That all carpenters now receiving more than $2.30 shall be advanced 5.9 per cent.

[b] *Provided*, That any class of outside day labor now receiving $1.91 or more per day shall be advanced 5.9 per cent. This provision only applies to outside labor not otherwise enumerated.

Miners shall have the right to send out their dull tools on top of loaded cars and the company shall deliver same to blacksmith shop for sharpening, and no man be allowed to carry tools up or down shaft. In slopes the company shall deliver the same to parting or bottom. The company shall not be responsible for tools.

Any underground employee not on hand to go down to work at the hour for commencing work shall not be entitled to go below except at the convenience of the company.

When an employee is sick or injured he shall be given a cage at once. When a cage load of men come to the bottom of the shaft who have been prevented from working by reason of falls or other things over which they have no control, they shall be given a cage at once. For the accommodation of individual employees less than a cage load who have been prevented from working as above cage will be run mid-forenoon, noon, and mid-afternoon to each working day: *Provided, however,* That the foregoing shall not be permitted to enable men to leave their work for other than the reasons stated above.

The sinking of slopes and driving narrow work through faults shall be left to local union and mine management for adjustment.

All double-shift places to be paid 28 cents per yard extra.

All wet entries, rooms, slopes, slope air courses, and all other work connected with the slopes shall be left to local union and superintendent or manager for agreement of price.

Frozen or seamy coal, stuck top or bottom, shall be deficient work, and shall be paid for extra, the same to be determined by mine committee and pit boss. If they fail to agree the miner shall be given an average place in the mine.

There shall be no deduction for school purposes except authorized by the individuals.

For the health and safety of the miners' lives, air courses shall be kept up with the entries as near as possible, and crosscuts shall be driven every 40 feet; where gas exists, they shall be driven every 30 feet. No room shall be turned inside the last crosscut.

Scale price for blacksmithing miners' tools and machine mine tools.

Three-fourths of 1 per cent on gross earnings for blacksmithing of miners' tools, and three-eighths of 1 per cent on gross earnings for machine coal loaders' tools.

All sharpening and repairing of tools shall be done as promptly as possible.

The present conditions in regard to double and single work shall prevail.

Any employee absenting himself from work two days and not reporting for work on the morning of the third day shall forfeit his right to his working place, unless excused by mine foreman, but shall be given another place on turn; provided, however, this shall not apply in case of sickness.

Where a fall occurs in any working place the company shall make preparations to clean up same within four hours from time of notice; failing to do so the miner or miners affected shall clean up same, company paying at the rate of $2.56 per shift.

Price for moving all draw slate and rock exceeding 2 inches in thickness, 2½ cents per inch per running yard for each 5 feet in width, and all over and above to be paid accordingly. This applies to all mines except where there is a special contract.

Where rooms are driven up narrow on account of bad top, the yardage shall be same as that in air courses, measurements to be made from the entry; and when room is widened out one-half room turning shall be paid. Where bottom is taken up entry yardage shall be paid. This does not apply in rooms that have been widened out, then narrowed up and renecked, but in these cases the prices shall be the 1903 rate.

When a car leaves working place it is in charge of the company and average weight shall be paid for broken cars. Such cars shall be reported by the man that dumps the coal. The company shall keep all cars in good repair.

All coal 4 feet and over where it comes down to under a thickness of 3 feet 4 inches shall be declared deficient work. This applies to Arkansas and the Indian Territory.

Where cars are delivered at working face all timber and rails shall be delivered there.

Where powder is taken into the mine in kegs it shall be delivered to the working place; otherwise it shall be handled according to the methods in vogue at the various mines.

When any employee shall be requested to fill the place of another employee, as specified herein, he shall receive the wages of the employee whose place he takes, plus 28 cents; provided further, that it is not compulsory on any man who may not wish to take such place.

All questions that have been left to the president of the United Mine Workers of America, District 21, and commissioner of the Operators' Association, or to arbitration shall become a part of this contract and be binding upon both parties when the same have both been decided and agreed upon by the said president and commissioner, or by arbitration; and the operators shall furnish the district secretary of the United Mine Workers of America and also post at the mines the prices to be paid on and after June 16, 1906, based hereon.

Color shall be no bar to employment.

In behalf of the Southwestern Interstate Coal Operators' Association.

W. C. Perry,
President.
S. J. Tonkin,
Secretary.

In behalf of the miners.

Pete Hanraty,
President District No. 21.
S. F. Brackney,
Secretary District No. 21.

MINES, OPENINGS, AND EXPOSURES OF COAL.

The following table presents in condensed form data of interest in regard to the mines, openings, and exposures of coal in the Arkansas field.

Table of mines, openings, and exposures of coal.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T. N.	R. W.	Section.						
9	32	13, SW. ¼ NE. ¼.		Prospect.	Coal, 6 in.	Hartshorne.	U. S. Geol. Survey.	
8	32	2, SE. ¼ SW. ¼.	Herman.	Old strip.	Shale roof. Bone, 12 in. Coal 10 in. Shale floor.	Fort Smith.	U. S. Geol. Survey.	
		9, SW. ¼.		Gas well, 500 ft.	Coal, 2 ft.	Hartshorne.	H. E. Kelly.	
		25, SE. ¼.		Old shaft.	No record.	Hartshorne.	U. S. Geol. Survey.	
		25, SE. ¼ SW. ¼.		Old shaft.	No record.	Hartshorne.	U. S. Geol. Survey.	
		35, SE. ¼.		Old strip.	Shale roof. Coal, 9 in. Shale, 1 in. Coal, 5 in.	Hartshorne.	U. S. Geol. Survey.	
		36, NW. ¼ NE. ¼.	Angelo Birt.	Strip.	Shale roof. Coal, 2 ft. Shale, 3 in. Coal, 4 in.	Hartshorne.	U. S. Geol. Survey.	
7	32	1, NE. ¼.		Old strip.	Coal, 1 ft. 8 in.	Hartshorne.	Citizen.	
		10, SW. ¼ SW. ¼.		Drill hole, 190 ft.	Coal, 2 ft. 4 in. Shale, 6 in. Coal, 6 in.	Hartshorne.	Citizen.	

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T. N.	R. W.	Section.						
7	32	14, SE. ¼ NE. ¼.		Drill hole, 192 ft.	Shale roof. Coal, 1 ft. 4 in. Shale, 2 in. Coal, 6 in. Gray band, 1 in. Coal, 11 in.	Hartshorne.	Central Coal and Coke Co.	12 ft. below this is a 4-ft. bed of shaly coal.
		33, SE. ¼ SW. ¼.		Drill hole, 276 ft.	Shale roof. Coal, 1 ft. Clay, 3 in. Coal, 2 ft. 3 in.	Hartshorne.	Central Coal and Coke Co.	
		34, NE. ¼.		Drill hole, 347 ft.	Shale roof. Coal, 2 ft. 2 in. Shale, 1 in. Coal, 11 in. Shale floor.	Hartshorne.	Central Coal and Coke Co.	
		34, NE. ¼ SW. ¼.	No. 26, Central Coal and Coke Co.	Shaft, 350 ft.	Shale roof. Coal, 3 ft. Shale floor.	Hartshorne.	Central Coal and Coke Co.	
		36, SE. ¼ NW. ¼.	No. 18, Western Coal and Mining Co.	Shaft, 260 ft.	Shale roof. Coal, 3 ft. 2 in. Shale, 2 in. Coal, 1 ft. 2 in. Shale floor.	Hartshorne.	Western Coal and Mining Co.	Coal has live luster, is hard, varies from 3 ft. 2 in. to 6 ft. in thickness.
		4, lot 4.	No. 20, Central Coal and Coke Co.	Shaft.	Shale roof. Coal, 2 ft. 5 in. Shale, 1 in. Coal, 1 ft. 2 in.	Hartshorne.	Central Coal and Coke Co.	Coal and parting vary in thickness.

		5, S. ½.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	
6	32	21, SW. ¼ NW. ¼.	Hackett City Smokeless Coal Co.	Slope.	Shale roof. Coal, 3 ft. 8 in. Sandstone floor.	Hartshorne.	U. S. Geol. Survey.	
		22, SW. ¼.		Old shaft.	Coal, 3 ft.	Hartshorne.	Arkansas Geol. Survey.	
		24.		Drill hole.	Shale roof. Coal, 1 ft. 2 in. Sandstone floor.	Hartshorne.	Cherokee Construction Co.	
		11, SW. ¼ SE. ¼.		Drill hole, 240 ft.	Shale roof. Coal, 2 ft. 8 in.	Hartshorne.	Cherokee Construction Co.	51 ft. above this is a 6-ft. bed of coal and bone.
		12, SE. ¼ SW. ¼.		Drill hole, 187 ft.	Shale roof. Coal, 3 ft. 1 in. Shale floor.	Hartshorne.	Cherokee Construction Co.	45 ft. above this is a 5 ft. 6 in. bed of coal and bone.
		12, SW. ¼ SW. ¼.		Drill hole, 186 ft.	Shale roof. Coal, 2 ft. 7 in. Bone, 11 in.	Hartshorne.	Cherokee Construction Co.	39 ft. above this is a 5 ft. 6 in. bed of coal and bone.
5	32	13, SW. ¼.		Old shaft, 170 ft.	Shale roof. Coal, 3 ft. 4 in.	Hartshorne.	Dallas Coal Co.	55 ft. above this is another bed of coal.
		14, NE. ¼ NE. ¼.		Drill hole, 163 ft.	Shale roof. Coal, 2 ft. 9 in. Bone, 8 in. Shale floor.	Hartshorne.	Cherokee Construction Co.	45 ft. above this is a 5 ft. 6 in. bed of bone, coal, and shale.
		14, SE. ¼ SE. ¼.		Drill hole, 203 ft.	Shale roof. Coal, 2 ft. 7 in. Bone, 8 in.	Hartshorne.	Cherokee Construction Co.	48 ft. above this is a 4 ft. 6 in. bed of dirty coal.

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T. N.	R. W.	Section.						
5	32	14, SW. ¼ NE. ¼.		Drill hole, 177 ft.	Shale roof. Coal, 3 ft. 3 in. Shale floor.	Hartshorne.	Cherokee Construction Co.	45 ft. above this is a 3 ft. 4 in. bed of coal, bone, and shale.
		14, NW. ¼ NE. ¼.		Drill hole, 183 ft.	Shale roof. Coal, 2 ft. 9 in. Bone, 8 in. Shale floor.	Hartshorne.	Cherokee Construction Co.	41 ft. above this is a 6 ft. 10 in. bed of coal, shale, and bone.
		14, SW. ¼ NW. ¼.		Drill hole, 239 ft.	Shale roof. Coal, 2 ft. 11 in. Shale floor.	Hartshorne.	Cherokee Construction Co.	40 ft. above this is a 3 ft. 3 in. bed of dirty coal.
		22, NE. ¼ NE. ¼.		Drill hole, 456 ft.	Shale roof. Coal, 3 ft. 3 in. Sandstone floor.	Hartshorne.	Cherokee Construction Co.	50 ft. above this is a 4 ft. 2 in. bed of coal and bone.
		1, lot 4 or 5.	No. 4, Cherokee Construction Co.	Shaft, 170 ft.	Sandstone roof. Coal, 4 ft. 3 in. Shale, 8 in. Coal, 3 ft. 6 in. Shale floor.	Hartshorne.	Cherokee Construction Co.	
		1, lot 8.		Old slope.	No record.	Hartshorne.	U. S. Geol. Survey.	
		1, lot 12.		Old slope.	No record.	Hartshorne.	U. S. Geol. Survey.	
		2, NE. ¼.		Old slope.	No record.	Hartshorne.	U. S. Geol. Survey.	
		2, SE. ¼ NW. ¼.		Old slope.	No record.	Hartshorne.	U. S. Geol. Survey.	

4	32	2, W. ½ SW. ¼.		*Old slope.*	No record.	Hartshorne.	U. S. Geol. Survey.	
		6, lot 13.		Crop.	-	Charleston.	U. S. Geol. Survey.	Blossom.
		10, SE. ¼ NW. ¼.	No. 4, Bolen-Darnall Coal Co.	Slope.	Shale roof. Coal, 4 ft.	Hartshorne.	U. S. Geol. Survey.	
		10, SW. ¼ SW. ¼.	No. 2, Bolen-Darnall Coal Co.	Slope.	Shale roof. Coal, 4 ft.	Hartshorne.	U. S. Geol. Survey.	
		13, NW. ¼ SE. ¼.	Arkansas Smokeless Coal Co.	Slope	Sandstone roof. Coal, 3 ft. 8 in. Shale, 1 ft. 4 in. Coal, 8 in. Shale floor.	Hartshorne.	U. S. Geol. Survey.	2 in. bone in top bench. Lower bench not mined.
		14, NE. ¼ SE. ¼.	Patterson Coal and Mining Co.	Slope.	Sandstone roof, Coal, 3 ft. 6 in. Clay, 10 in. Coal, 10 in. Shale floor.	Hartshorne.	U. S. Geol. Survey.	3 ft. or more of "black jack" lies below the coal.
		15, N. ½ NW. ¼.	No. 4, Central Coal and Coke Co.	Slope.	Shale roof. Coal, 4 ft.	Hartshorne.	U. S. Geol. Survey.	
		17, SW. ¼ NW. ¼.		Drill hole.	Sandstone roof. Coal, 4 ft. 3 in. Shale floor.	Hartshorne.	Cherokee Construction Co.	110 ft. above this is a 5-ft. bed of coal and bone.
		22, NW. ¼ NW. ¼.	Central Coal and Coke Co.	Drill hole.	Shale roof. Coal, 3 ft. 6 in. Shale, 3 in. Coal, 2 in. Shale, 7 in. Coal, 11 in. Bone, 1 ft. 8 in.	Hartshorne.	Cherokee Construction Co.	52 ft. above this is a 5 ft. 9 in. bed of bone and coal. 100 ft. above is a 5-ft. bed of shale and coal.

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T. N.	R. W.	Section.						
3	32	19, SW. ¼.	Witte Coal Co.	Slope.	Shale roof. Coal, 5 ft. Shale, 7 in. Coal, 2 ft. 6 in. Shale floor.	Hartshorne.	D. Lytle.	Only the upper bench is mined.
		21, NE. ¼ NE. ¼.	Davidson.	Slope.	Shale roof. Coal, 4 ft. Shale, 8 in. Coal, 3 ft. 4 in. Shale floor.	Hartshorne.	U. S. Geol. Survey.	Partings contain more or less coal.
		21, NW. ¼ NE. ¼.		Slope.	Shale roof. Coal, 7 in. Shale, 1 in. Coal, 1 ft. 3 in. Shale, 4 in. Coal, 1 ft. 9 in. Shale, 8 in. Coal, 1 ft. 9 in. Shale, 1 ft. 6 in. Bone, 6 in. Coal, 3 in. Shale floor.	Hartshorne.	U. S. Geol. Survey.	Partings contain thin seams of coal. Coal beds contain shale bands.
		21, NE. ¼ NW. ¼.	Seymour Coal Co.	Slope.	Shale roof. Coal, 2 ft. Shale, 3 in. Coal, 2 ft. Shale, 2 ft. Coal, 2 ft. Shale, 2 ft. 6 in. Coal, 4 ft.	Hartshorne.	U. S. Geol. Survey.	Only the lowest bench is worked.

9	31	3, NE. ¼.		Crop.	Sandstone roof. Coal, 4 in. Sandstone floor.	Hartshorne.	U. S. Geol. Survey.	Exposed in railroad cut.
		13, NE. ¼.	Sullivant.	Crop.	Shale roof. Coal, 1 ft.	Fort Smith.	U. S. Geol. Survey.	
		16, NW. ¼.	Hendricks.	Old slope.	Coal, 2 ft.	Fort Smith.	Arkansas Geol. Survey.	Possibly another bed 5 ft. below.
8	31	28, SW. ¼.		Slope.	Shale roof. Coal, 1 ft. 11 in.	Hartshorne.	U. S. Geol. Survey.	
		30, NW. ¼.		Shaft, 85 ft.	Shale roof. Coal, 1 ft. 10 in. Shale, 4 in. Coal, 1 ft.	Hartshorne.	U. S. Geol. Survey.	
		30, SW. ¼		Shaft, 42 ft.	Same as next above.	Hartshorne.	Citizen.	
		30, SW. ¼.	Montgomery and Jones.	Slope.	Shale roof. Coal, 1 ft. 10 in. Shale, 1½ in. Coal, 8 in.	Hartshorne.	U. S. Geol. Survey.	Parting varies up to 1½ in.
7	31	1, N. ½.		Old slopes.	Shale roof. Coal, 1 ft. 8 in.	Charleston.	U. S. Geol. Survey.	Coal varies from 14 in. to 20 in.
		3, NE. ¼ SW. ¼.		Prospect.	Shale roof. Coal, 1 ft. 6 in.	Charleston.	U. S. Geol. Survey.	
		13, SW. ¼.	Bostick.	Old slope.	Coal, 2 ft. 10 in. Parting.	Hartshorne.	U. S. Geol. Survey.	

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by	Remarks.
T. N.	R. W.	Section.						
7	31	17, NE. ¼ NW. ¼.		Drill hole, 702 ft.	Coal, 1 ft. 3 in. Shale, ½ in. Coal, 1 ft. Shale, 4½ in. Coal, 1 ft. 7 in.	Hartshorne.	Cherokee Construction Co.	
		19, SW. ¼ NE. ¼.		Drill hole, 600 ft.	Shale roof. Coal, 2 ft. 2 in. Shale, 1 in. Coal, 1 ft. 6 in. Shale floor.	Hartshorne.	Cherokee Construction Co.	
		21, NE. ¼ NW. ¼.		Drill hole, 690 ft.	Coal, 3 ft. 0 in. Parting, 2½ in.	Hartshorne.	Western Coal and Mining Co.	
		22, SW. ¼ SW. ¼.		Drill hole, 89 ft.	Coal, 3 ft. 9 in. Parting, 1 in.	Hartshorne.	Western Coal and Mining Co.	
		22, SE. ¼ NE. ¼.		Drill hole, 25 ft.	Coal, 3 ft. 7 in. Parting, 3 in.	Hartshorne.	Western Coal and Mining Co.	
		22.		Drill hole, 805 ft.	Coal, 6 ft.	Hartshorne.	Western Coal and Mining Co.	Location in section not known.
		28, NE. ¼ SW. ¼.		Drill hole, 198 ft.	Coal, 4 ft. 5 in.	Hartshorne.	Western Coal and Mining Co.	
		31, SW. ¼ NW. ¼.		Drill hole, 271 ft.	Coal, 4 ft. 5 in. Parting, 8 in.	Hartshorne.	Western Coal and Mining Co.	
		31, NW. ¼ SW. ¼.		Drill hole, 129 ft.	Coal, 4 ft. 7 in. Parting, 5 in.	Hartshorne.	Western Coal and Mining Co.	

		32, NE. ¼ NE. ¼.		Drill hole, 204 ft.	Coal, 4 ft.	Hartshorne.	Western Coal and Mining Co.	
		32, SE. ¼ NE. ¼.		Drill hole, 60 ft.	Coal, 5 ft. Parting, 1 in.	Hartshorne.	Western Coal and Mining Co.	
		32, SW. ¼ NE. ¼.		Drill hole, 77 ft.	Coal, 5 ft. 4 in. Parting, 1½ in.	Hartshorne.	Western Coal and Mining Co.	
		32, SW. ¼ SW. ¼.	Western Coal and Mining Co., No. 17.	Shaft, 212 ft.	Shale roof. Coal, 3 ft. Shale, 4 in. Coal, 3 ft.	Hartshorne.	U. S. Geol. Survey.	Some sulphur and gray bands in coal.
6	31	12 NW. ¼ NE. ¼.	Greenwood Coal and Lumber Co., No. 1.	Slope.	Shale roof. Coal, 3 ft. Parting, up to 6 in. Coal, 3 ft. Sandstone floor.	Hartshorne.	U. S. Geol. Survey.	Coal varies in thickness from 4 ft. to 7 ft.
		12, SE. ¼ SW. ¼.		Drill hole, 13 ft.	Coal, 3 ft. 1 in. Parting, 2 in.	Hartshorne.	Western Coal and Mining Co.	
		12, SW. ¼ SE. ¼.		Drill hole, 138 ft.	Coal, 3 ft. 5 in.	Hartshorne.	Western Coal and Mining Co.	Bony coal; contains sulphur.
		12, NW. ¼ SE. ¼.		Drill hole, 75 ft.	Coal, 3 ft.	Hartshorne.	Western Coal and Mining Co.	
		12, NW. ¼ SE. ¼.		Drill hole, 112 ft.	Coal, 6 ft. 7 in. Parting, 1 in.	Hartshorne.	Western Coal and Mining Co.	
		12, SE. ¼ SW. ¼.		Drill hole, 16 ft.	Coal, 2 ft. 2 in.	Hartshorne.	Western Coal and Mining Co.	
		12, SE. ¼ SW. ¼.		Drill hole, 11 ft.	Coal, 3 ft.	Hartshorne.	Western Coal and Mining Co.	

Table of mines, openings, and exposures of coal—**Continued.**

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T. N.	R. W.	Section.						
		12, NE. ¼ SE. ¼.		Drill hole, 215 ft.	Coal, 7 ft. 7 in. Partings, 5 in.	Hartshorne.	Western Coal and Mining Co.	One 4 in. and one 1 in. parting.
		12, NW. ¼ NW. ¼		Drill hole, 15 ft.	Coal, 2 ft. 11 in. Shale floor.	Hartshorne.	Western Coal and Mining Co.	
		12, NW. ¼ SE. ¼.		Drill hole, 80 ft.	Shale roof. Coal, 3 ft. Shale floor.	Hartshorne.	Cherokee Construction Co.	
		12, SE. ¼ NE. ¼.		Drill hole, 125 ft.	Shale roof. Coal, 3 ft. 3 in. Parting, 1 in. Coal, 3 ft. 4 in.	Hartshorne.	Cherokee Construction Co.	
		12, SE. ¼ SW. ¼.		Drill hole, 10 ft.	Coal, 2 ft. 5 in. Shale, 2 in. Coal, 8 in.	Hartshorne.	Cherokee Construction Co.	
		12, SW. ¼ SE. ¼.		Drill hole, 150 ft.	Shale roof. Coal, 3 ft. 5 in. Shale floor.	Hartshorne.	Cherokee Construction Co.	Coal is bony and contains sulphur.
6	31	13, NE. ¼ NE. ¼.		Drill hole, 39 ft.	Coal, 2 ft. 7 in.	Hartshorne.	Western Coal and Mining Co.	
		13, NE. ¼ NW. ¼.		Drill hole, 40 ft.	Shale roof. Coal, 2 ft. 7 in. Shale floor.	Hartshorne.	Cherokee Construction Co.	

		17, S. ½ NW. ¼	Skinner and Knott.	Slope.	Shale roof. Coal, 3 ft. Sandstone floor.	Hartshorne.	U. S. Geol. Survey.	Coal varies between 2 ft. 5 in. and 4 ft.
		18, NE. ¼ SW. ¼	Swofford.	Slope.	Shale roof. Coal, 2 ft. 8 in.	Hartshorne.	U. S. Geol. Survey.	Coal varies between 2 ft. 8 in. and 2 ft. 10 in.
		18, SW. ¼.	Bates and McWilliams	Shaft, 70 ft.	Shale roof. Coal, 2 ft. 10 in. Sandstone floor.	Hartshorne.	U. S. Geol. Survey.	Coal varies between 2 ft. 8 in. and 3 ft.
		21, NE. ¼.		Slope.	Shale roof. Coal, 2 ft. 6 in. Sandstone floor.	Hartshorne.	U. S. Geol. Survey.	A bed of bony coal lies 50 ft. below this.
		21, N. ½ SW. ¼.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom.
		29, SW. ¼.		Old workings.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom.
5	31	5, SE. ¼.		Prospect.	Coal.	Hartshorne.	U. S. Geol. Survey.	
		7, SE. ¼ SE. ¼.	Irby Coal Co.	Slope.	Sandstone roof. Coal, 3 ft. Shale floor.	Hartshorne.	U. S. Geol. Survey.	
		8, NE. ¼ NE. ¼.	Moran Coal Co.	Slope.	Shale roof. Coal, 3 ft. 4 in. Sandstone floor.	Hartshorne.	U. S. Geol. Survey.	
		18, SW. ¼.	Cherokee Construction Co.	Slope No. 5.	Coal, 3 ft. 4 in.	Hartshorne.	Cherokee Construction Co.	Coal variable in thickness.
		19, NW. ¼ NW. ¼.	Branner Coal Co.	Shaft, 60 ft.	Shale roof. Coal, 3 ft. 6 in.	Hartshorne.	U. S. Geol. Survey.	

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T. N.	R. W.	Section.						
5	31	19, NE. ¼ NW. ¼.	C. C. Woodson.	Strip.	Shale roof. Coal, 3 ft. 7 in. Shale floor.	Hartshorne.	U. S. Geol. Survey.	
		19, NE. ¼ NE. ¼.		Strip.	Shale roof. Coal, 3 ft. Shale floor.	Hartshorne.	U. S. Geol. Survey.	
		19, E. ½ SE. ¼.	Denman Coal Co.	Shaft 50 ft.	Shale roof. Coal, 3 ft. Shale floor.	Hartshorne.	U. S. Geol. Survey.	
		19, SW. ¼.		Drill hole, 253 ft.	Shale roof. Coal, 3 ft. 5 in. Sandstone floor.	Hartshorne.	Cherokee Construction Co.	58 ft. above this is another bed of coal.
		19, SE. ¼ SW. ¼.		Drill hole, 270 ft.	Shale roof. Coal, 3 ft.	Hartshorne.	Cherokee Construction Co.	55 ft. above is another bed.
		20, NW. ¼ SW. ¼.	Dallas Coal Co.	Shaft, 60 ft.	Sandstone roof. Coal, 3 ft. Shale floor.	Hartshorne.	U. S. Geol. Survey.	
		20, NE. ¼ SW. ¼.	C. C. Turnipseed.	Slope.	Sandstone roof. Coal, 3 ft.	Hartshorne.	U. S. Geol. Survey.	
		20, S. ½ NW. ¼.	Dallas Coal Co.	Shaft, 24 ft.	Sandstone roof. Coal, 3 ft.	Hartshorne.	U. S. Geol. Survey.	Blacksmithing coal.
		21, SE. ¼.		Strip.	Shale roof. Coal, 3 ft. 6 in.	Hartshorne.	U. S. Geol. Survey.	

		21, SE. ¼ NE. ¼.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom.
		22, SW. ¼.	G. W. Crabtree.	Slope.	Sandstone roof. Coal, 4 ft. 6 in. Parting, 1 ft. Coal, 6 in. Parting, 2 in. Coal, 1 ft. 10 in.	Hartshorne.	U. S. Geol. Survey.	Coal is exposed in several places near here.
		26, NW. ¼ NE. ¼.	Central Coal and Coke Co., No. 2.	Shaft, 49 ft.	Shale roof. Coal, 4 ft. Parting, 9 in. Coal, 6 in. Parting, 3 in. Coal, 2 ft. 6 in. Shale floor.	Hartshorne.	Central Coal and Coke Co.	Benches are variable in thickness.
		27, NW. ¼ SW. ¼.	Central Coal and Coke Co., No. 3.	Shaft, 23 ft.	Shale roof. Coal, 4 ft. Parting, 9 in. Coal, 6 in. Parting, 3 in. Coal, 2 ft. 6 in. Shale floor.	Hartshorne.	Central Coal and Coke Co.	Coal has sandstone roof on west side of shaft.
4	31	12, SW. ¼.	Bethel.	Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom.
		15, NW. ¼.		Old workings.	No record.	Hartshorne.	U. S. Geol. Survey.	
		16, SW. ¼.		Old slope.	No record.	Hartshorne.	U. S. Geol. Survey.	
		17, NE. ¼ SW. ¼.	Claborn.	Prospect.	Coal, 10 in. Shale, 4 in. Shaly coal, 8 in. Coal, 1 ft. 7 in. Shale, 2 ft. 6 in. Coal, 2 ft. 4 in. Shale, 2 ft. Coal, 4 in. to 1 ft. Shale, 8 ft. Coal, 3 in.	Hartshorne.	Arkansas Geological Survey.	

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T. N.	R. W.	Section.						
4	31	18 E. ½ SE. ¼.	Chasteen.	Prospect.	Coal, 1 ft. Parting, 3 in. Coal, 6 in. Parting, 1 in. Coal, 2 in. Parting, 2 in. Coal, 2 ft. 6 in. Parting, 1 ft. 11 in. Coal, 8 in. Parting, 4 in. Coal, 2 ft.	Hartshorne.	U. S. Geol. Survey.	All of the lowest bench of coal was not seen, though it is probably 2 ft., as reported.
3	31	1, SE. ¼ NE. ¼.		Prospect.	Shale roof. Coal, 3 in. Parting, 7 in. Coal, 2 in. Parting, 8 in. Coal, 3 in. Parting, 3 in. Coal, 4 in. Parting, 2 in. Coal, 1 ft. Shale floor.	Hartshorne.	U. S. Geol. Survey.	All of the bed is not exposed.
		8, NE. ¼ SW. ¼.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom.
		9, NW. ¼.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom.
		10, NW. ¼.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom.
		17, NW. ¼.		Drill hole, 391 ft.	Shaly coal, 1 ft. 7 in.	Hartshorne.	Central Coal and Coke Co.	

9	30	17, NW. ¼.			Coal, 9 in.	300 ft. above Hartshorne.	Central Coal and Coke Co.	Same drill hole as one next above.
		19.	Gross.	Drill hole.	Coal, 10 in.	Hartshorne.	G. P. Gross.	
		33, SE. ¼ NE. ¼.	Graves.	Prospect.	Coal, 1 ft. 6 in.	Fort Smith.	U. S. Geol. Survey.	
8	30	22, NE. ¼.		Crop.	Coal.	Fort Smith.	U. S. Geol. Survey.	Blossom.
7	30	7.		Drill hole, 698 ft.	Bone coal, 4 ft. Coal, 4 ft.	Hartshorne.	Cherokee Construction Co.	On the Edenborn farm.
		14, NW. ¼ SW. ¼.		Drill hole, 268 ft.	Shale roof. Bone coal, 9 in. Coal, 2 ft. Shale floor.	Hartshorne.	Cherokee Construction Co.	
		24, S. ½ NE. ¼.		Old working.	Coal, 1 ft. 6 in.	Hartshorne.	Citizen.	
		25, NW. ¼.		Old working.	Coal, 1 ft. 4 in.	Hartshorne.	Citizen.	
		32, SE. ¼ SE. ¼.	McConnel.	Old working.	Shale roof. Coal, 4 in. Shale, 1 in. Coal, 2 ft. 5 in.	Hartshorne.	Arkansas Geol. Survey.	
6	30	5, lot 5.		Drill hole, 100 ft.	Shale roof. Coal, 6 ft. 10 in. Shale floor.	Hartshorne.	Western Coal and Mining Co.	Bands of coal in roof and floor.
		5, lot 5.		Drill hole, 36 ft.	Shale roof. Coal, 1 ft. 9 in. Shale floor.	Hartshorne.	Western Coal and Mining Co.	
		5, lot 5.		Drill hole, 50 ft.	Shale roof. Coal, 2 ft. 3 in. Shale floor.	Hartshorne.	Western Coal and Mining Co.	

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T. N.	R. W.	Section.						
6	30	5.		Drill hole, 345 ft.	Shale roof. Coal, 2 ft. 9 in. Bone coal, 3½ in. Coal, 2 ft. 6 in. Shale, 2½ in. Coal, 3½ in. Shale, 1 ft. Coal, 4½ in. Bone coal, 2 in. Coal, 1 in. Parting, 1 in. Coal, 1½ in. Bone coal, 3 in. Coal, 1 ft. 7½ in.	Hartshorne.	Western Coal and Mining Co.	Diamond drill hole on the McCord farm.
		6, lot 13.		Drill hole, 25 ft.	Shale roof. Coal. Shale floor.	Hartshorne.	Cherokee Construction Co.	
		6, SW. ¼ SW. ¼.		Drill hole, 20 ft.	Coal, 5 ft. 6 in. Shale floor.	Hartshorne.	Cherokee Construction Co.	
		6, lot 8.		Drill hole, 38 ft.	Shale roof. Coal, 1 ft. 6 in. Shale, 2 in. Coal, 2 ft. 7½ in.	Hartshorne.	Cherokee Construction Co.	½-inch sulphur band in lower bench.
		6, SE. ¼ NE. ¼.	Fidelity Fuel Co., Banner mine.	Slope.	Shale roof. Coal, 5 ft. 3 in. Bone coal, 3 in. Sandstone floor.	Hartshorne.	U. S. Geol. Survey.	

		7, lot 4.		Drill hole, 315 ft.	Sandstone roof. Coal, 3 ft. Shale, 1 ft. 5 in. Coal, 4 ft. 1½ in. Shale floor.	Hartshorne.	Cherokee Construction Co.	
		19, N. ½.		Old working.	Coal.	Hartshorne.	U. S. Geol. Survey.	No record.
4	30	8, S. ½.	Lewis Pogue.	Old working.	Coal.	Hartshorne.	Citizen.	In two benches.
		9, SW. ¼.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom.
		13, NE. ¼ SW. ¼.		Drill hole, 320 ft.	Coal, 6 in. Fire-clay floor.	Fort Smith.	Cherokee Construction Co.	
3	30	3, NW. ¼.		Prospect.	Coal.	Hartshorne.	U. S. Geol. Survey.	
		4, NW. ¼.	Holloway.	Well.	Coal.	Hartshorne.	Citizen.	Coal struck in well.
		5, NE. ¼.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom.
		6, W. ¼.		Prospect.	Coal.	Hartshorne.	U. S. Geol. Survey.	
10	29	10, N. ½ SE. ¼.		Crop.	Coal, 5 in.	Hartshorne.	U. S. Geol. Survey.	
		21, SW. ¼.		Old strip.	Coal, 1 ft.	Hartshorne.	U. S. Geol. Survey.	
		36, N. ½.		Crop.	Clay roof. Coal, 1 ft. 1 in. Bone coal, 5 in.	Hartshorne.	U. S. Geol. Survey.	Exposed in road.
		36, E. ½.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Exposed in road.
8	29	11, SE. ¼	Vesta.	Old working.	Coal.	Hartshorne.	Citizen.	

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T. N.	R. W.	Section.						
7	29	13, NW. ¼ NW. ¼.		Prospect, 16 feet deep.	Coal.	Charleston.	Citizen.	
		16, NE. ¼ NE. ¼.		Old workings.	Coal; no record.	Charleston.	U. S. Geol. Survey.	
		16, W. ½.		Old workings.	Coal; No record.	Charleston.	U. S. Geol. Survey.	
		20, NW. ¼.	Coal Ridge.	Old slope.	Shale roof. Coal, 1 ft. 6 in. Shale floor.	Charleston.	U. S. Geol. Survey.	
		25, SW. ¼.		Crop.	Coal.	Paris.	U. S. Geol. Survey.	Blossom.
		27, NW. ¼.		Strip.	Coal, 1 ft. 2 in.	Paris.	Citizen.	
		31 SW. ¼.	Bean.	Strip.	Coal, 1 ft. 8 in.	Charleston.	Arkansas Geol. Survey.	
6	29	5, SW. ¼ NE. ¼.	McClellan.	Drill hole, 28 ft.	Coal, 1 ft. 7½ in.	Hartshorne.	McClellan.	Coal crops out near.
		6, S. ½.	Langston.	Strip.	Coal, 1 ft. 6 in.	Fort Smith.	Arkansas Geol. Survey.	
4	29	7, SE. ¼.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom in road.
9	28	4, W. ½.	Lewis.	Old working.	Coal, 1 ft. 2 in.	Hartshorne.	Arkansas Geol. Survey.	
		6, SW. ¼ NW. ¼.	Anderson.	Prospect.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	

8	28	8, SE. ¼ SE. ¼.	Logan.	Prospect.	Coal.	Hartshorne.	Logan.	
		11, NW. ¼.		Well.	Coal, 1 ft. 6 in.	Hartshorne.	Citizen.	Reported as struck in a well.
		17, E. ½.		Crop.	Coal.	Spadra.	Citizen.	
		28, SW. ¼.	Minden.	Strip.	Coal, 1 ft. 8 in.	Charleston.	U. S. Geol. Survey.	
		29, SW. ¼.		Crop.	Coal, 1 ft. 5 in.	Charleston.	U. S. Geol. Survey.	
		31, NW. ¼ NW. ¼.		Old strip.	Coal, 1 ft. 5 in.	Charleston.	U. S. Geol. Survey.	
		32, SW. ¼.		Crop.	Coal, 10 in.	Charleston.	U. S. Geol. Survey.	
		32, NW. ¼ SE. ¼.	Fealy.	Strip.	Coal, 1 ft. 8 in.	Charleston.	U. S. Geol. Survey.	
		34, SE. ¼.	Cotton.	Crop.	Coal, 1 ft. 8 in.	Charleston.	U. S. Geol. Survey.	
7	28	2, NE. ¼.		Crop.	Coal, 1 ft. 4 in.	Charleston.	U. S. Geol. Survey.	
		3, SE. ¼ NE. ¼.		Crop.	Coal.	Charleston.	U. S. Geol. Survey.	
		13, SW. ¼.		Crop.	Coal, 1 ft. 6 in.	Charleston.	U. S. Geol. Survey.	
		16, SW. ¼.		Old working.	Coal, 1 ft. 6 in.	Charleston.	U. S. Geol. Survey.	
		17, SE. ¼ NE. ¼.	Carter.	Slope.	Coal, 2 ft. 6 in.	Charleston.	C. C. Carter.	Reported to vary between 30 in. and 36 in.
		22, NW. ¼.		Prospect.	Coal.	Charleston.	U. S. Geol. Survey.	

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T. N.	R. W.	Section.						
7	28	22, SW. ¼ NE. ¼.		Prospect.	Coal.	Charleston.	U. S. Geol. Survey.	
		23, N. ½.		Prospect.	Coal, 1 ft. 8 in.	Charleston.	U. S. Geol. Survey.	
		24, NW. ¼.		Strip.	Coal, 1 ft. 6 in.	Charleston.	U. S. Geol. Survey.	
		24, NE. ¼.			Coal, 9 in.	Charleston.	U. S. Geol. Survey.	
		30, SE. ¼.		Slope.	Coal, 1 ft. 6 in.	Charleston.	U. S. Geol. Survey.	
		32, NW. ¼.		Prospect.	Coal, 1 ft. 10 in.	Charleston.	U. S. Geol. Survey.	
		33, NW. ¼.		Prospect.	Coal, 1 ft. 8 in.	Charleston.	U. S. Geol. Survey.	
		33, NE. ¼.		Prospect.	Coal.	Charleston.	U. S. Geol. Survey.	
10	27	3, SW. ¼.		Prospect.	Coal, 10 in.	Below Hartshorne.	U. S. Geol. Survey.	
		8, SE. ¼ NW. ¼.		Prospect.	Coal, 10 in.	Below Hartshorne.	U. S. Geol. Survey.	
		10, SW. ¼.		Prospect.	Coal.	Below Hartshorne.	U. S. Geol. Survey.	
		34, SE. ¼.		Crop.	Coal.	Below Hartshorne.	U. S. Geol. Survey.	

		36, NE. ¼.	Adams.	Crop.	Coal.	Below Hartshorne.	U. S. Geol. Survey.	
9	27	9, SE. ¼.		Drill hole, 258 ft.	Shaly coal, 2 in. Coal, 11 in. Shaly coal, 1 in. Coal, 11 in. Shale, 2 in. Coal, 10 in.	Below Hartshorne.	Central Coal and Coke Co.	
		11, NW. ¼.		Prospect.	Coal, 5 in.	Below Hartshorne.	U. S. Geol. Survey.	
		23, NE. ¼.		Prospect.	Coal.	Hartshorne.	U. S. Geol. Survey.	In two benches.
8	27	22, SE. ¼.		Prospect.	Coal, 1 ft. 2 in.	Charleston.	U. S. Geol. Survey.	
		30, NW. ¼.	Carpenter.	Prospect.	Coal, 1 ft. 10 in.	Charleston.	U. S. Geol. Survey.	
		35, SW. ¼.	Ockenfels.	Crop.	Coal, 6 in.	Paris.	U. S. Geol. Survey.	
		35, NE. ¼.			Coal, 10 in.	Paris.	Citizen.	
7	27	3, SW. ¼.		Strip.	Coal, 1 ft. 11 in.	Charleston.	Citizen.	
		10, NE. ¼.	Caulk's.	Prospect.	Coal, 1 ft. 1 in.	Charleston.	U. S. Geol. Survey.	Base of coal not seen.
		13, N. ½.		Prospect.	Coal.	Spadra.	U. S. Geol. Survey.	Blossom.
		14, NE. ¼.		Prospect.	Coal.	Hartshorne.	U. S. Geol. Survey.	Crops in road east of creek.
		18, SW. ¼.			Coal.	Charleston.	U. S. Geol. Survey.	
		19, W. ½.			Coal, 2 ft. 6 in.	Charleston.	U. S. Geol. Survey.	
		33, W. ½.		Prospect.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom.

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T.N.	R.W.	Section.						
10	26	12, SW. ¼.		Old working.	Coal.	Charleston.	U. S. Geol. Survey.	
		13, NE. ¼ NW. ¼.		Well, 27 ft.	Coal; no record.	Charleston.	N. G. Greer.	
		22.	Old Moomaw openings.	Slopes.	Coal, 1 ft. 10 in.	Charleston.	U. S. Geol. Survey.	Five or six openings.
		23, NW. ¼ SW. ¼.		Slope.	Coal, 1 ft. 10 in.	Charleston.	Adams.	
		23, SW. ¼ NW. ¼.		Slope.	Coal, 1 ft. 10 in.	Charleston.	Adams.	
		27, NW. ¼ NW. ¼.		Prospect.	Coal, 2 ft. 2 in.	Hartshorne.	Adams.	
		6, SE. ¼ SE. ¼.		Crop.	Coal, 6 in.	Below Hartshorne.	U. S. Geol. Survey.	Crops in railroad cut.
		7, SE. ¼.		Crop.	Coal.	Below Hartshorne.	U. S. Geol. Survey.	
		17, SW. ¼.	Garritz.	Slope.	Coal, 2 ft. 1 in.	Hartshorne.	U. S. Geol. Survey.	18 ft. above this is a 22-in. bed.
		20, NE. ¼ NW. ¼.		Drill hole, 457 ft.	Coal, 5 feet.	Below Hartshorne.	Western Coal and Mining Co.	
		21, SE. ¼ NW. ¼		Drill hole, 24 ft.	Coal, 6 in. Shale, 1 ft. 2 in. Coal, 2 ft.	Hartshorne.	Western Coal and Mining Co.	

21, SW. ¼ SW. ¼.		Drill hole, 66 ft.	Coal, 2 ft. 6 in. Shale, 4 in. Coal, 2 ft. 3 in.	Hartshorne.	Western Coal and Mining Co.	
22, NE. ¼ SW. ¼.		Drill hole, 258 ft.	Coal, 2 ft. Shale, 8 in. Coal, 2 ft. 2 in.	Hartshorne.	Western Coal and Mining Co.	
22, NW. ¼ SW. ¼.	No. 2, Western Coal and Mining Co.	Shaft, 185 ft.	Coal, 2 ft. 3 in. Shale, 3 in. Coal, 2 ft.	Hartshorne.	Western Coal and Mining Co.	Benches and partings variable.
23, NW. ¼ SE. ¼.		Drill hole.	Coal, 2 ft. 5 in. Shale, 1 ft. Coal, 2 ft.	Hartshorne.	Western Coal and Mining Co.	
23, SE. ¼ SE. ¼.	No. 3, Western Coal and Mining Co.	Shaft, 160 ft.	Coal, 2 ft. 8 in. Shale, 1 ft. 2 in. Coal, 2 ft. 7 in.	Hartshorne.	Western Coal and Mining Co.	Benches and partings variable.
24, NW. ¼ SW. ¼.		Drill hole, 116 ft.	Coal, 1 ft. 7 in. Shale, 3 ft. Coal, 1 ft. 11 in.	Hartshorne.	Western Coal and Mining Co.	
24, SW. ¼ SE. ¼.		Drill hole, 27 ft.	Coal, 4 ft. 6 in.	Hartshorne.	Western Coal and Mining Co.	
24 NE. ¼.		Old slope.	Coal, 1 ft.	Below Hartshorne.	U. S. Geol. Survey.	
25, SE. ¼.		Shaft.	Coal.	Hartshorne.	U. S. Geol. Survey.	
25, SW. ¼.	No. 5, Western Coal and Mining Co.	Shaft.	Coal.	Hartshorne.	U. S. Geol. Survey.	
26, SW. ¼ NE. ¼.		Drill hole, 36 ft.	Coal, 4 ft. 2 in.	Hartshorne.	Western Coal and Mining Co.	

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by.	Remarks.
T. N.	R. W.	Section.						
9	26	27, NE. ¼ NE. ¼.		Drill hole, 121 ft.	Coal, 2 ft. Shale, 6 in. Coal, 2 ft. 7 in.	Hartshorne.	Western Coal and Mining Co.	
		27, SE. ¼.		Drill hole, 100 ft.	Coal, 4 ft. 8 in.	Hartshorne.	Western Coal and Mining Co.	
		28 NE. ¼ NE. ¼.		Drill hole, 142 ft.	Coal, 2 ft. 8 in. Shale, 8 in. Coal, 2 ft.	Hartshorne.	Western Coal and Mining Co.	
		28, NE. ¼ SE. ¼.		Drill hole, 187 ft.	Coal, 4 ft.	Hartshorne.	Western Coal and Mining Co.	
		34, S. ½ NW. ¼.		Drill hole, 108 ft.	Coal, 1 ft.	Hartshorne.	Western Coal and Mining Co.	
8	26	26, SW. ¼ SW. ¼.		Crop.	Coal.	Paris.	U. S. Geol. Survey.	Blossom.
		28, SE. ¼.		Crop.	Coal.	Paris.	U. S. Geol. Survey.	Blossom.
		28, SW. ¼.		Crop.	Coal, 2 ft. 6 in.	Paris.	U. S. Geol. Survey.	
		29, SE. ¼.		Crop.	Coal.	Paris.	U. S. Geol. Survey.	Blossom.
		29, SW. ¼ SW. ¼.	Goldsworthy.	Old working.	Shale roof. Coal, 2 ft. 4 in.	Paris.	U. S. Geol. Survey.	
		31, NE. ¼.		Crop.	Coal.	Above Paris.	U. S. Geol. Survey.	Blossom in road.

		35, NW. ¼ NE. ¼.	Blue Ribbon.	Slope.	Coal.	Paris.	U. S. Geol. Survey.	
		35, E. ½.	Baxley.	Slope.	Coal.	Paris.	U. S. Geol. Survey.	
7	26	1, SW. ¼.	Domestic Coal Co.	Slope.	Shale roof. Coal, 2 ft. 6 in.	Paris.	U. S. Geol. Survey.	
		1, SE. ¼ NW. ¼.	Enterprise Mining Co.	Slope.	Shale roof. Coal, 2 ft. 2 in.	Paris.	U. S. Geol. Survey.	
		2. SE. ¼.	Spot Cash.	Shaft.	Coal.	Paris.	U. S. Geol. Survey.	
		3, SE. ¼.		Drill hole, 182 ft.	Coal, 2 ft. 8 in.	Paris.	Citizen.	
		6, SE. ¼.		Strip.	Coal.	Paris.	U. S. Geol. Survey.	
		10, SW. ¼ NW. ¼.	Union Coal Co.	Shaft.	Coal.	Paris.	U. S. Geol. Survey.	
		10, SE. ¼ NE. ¼.	Paris Coal Co.	Slope.	Coal, 2 ft. 2 in. Fire-clay floor.	Paris.	U. S. Geol. Survey.	
		15, NE. ¼.		Prospect.	Coal; no record.	Spadra.	U. S. Geol. Survey.	
10	25	18, W. ½.	Pete Close.	Slope.	Shale roof. Coal, 1 ft. 6 in.	Charleston.	U. S. Geol. Survey.	Reported to vary between 18 in. and 26 in.
		20, NE. ¼.	Philpott.	Slope.	Shale roof. Coal, 1 ft. 10 in.	Charleston.	U. S. Geol. Survey.	
		26, SE. ¼ SE. ¼.		Prospect.	Coal, 1 ft. 8 in.	Below Hartshorne.	U. S. Geol. Survey.	

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T.N.	R.W.	Section.						
10	25	31, SE. ¼.		Crop.	Coal, 1 ft.	Below Hartshorne.	U. S. Geol. Survey.	
		35, SE. ¼.		Crop.	Coal, 8 in.	Below Hartshorne.	U. S. Geol. Survey.	
		3, N. ½.		Crop.	Coal, 8 in.	Below Hartshorne.	U. S. Geol. Survey.	
		13, NW. ¼.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Exposed in road.
		19, NW. ¼ SE. ¼.	No. 4, Western Coal and Mining Co.	Shaft, 160 ft.	Shale roof. Coal, 3 ft. 5 in. Parting, 4 in.	Hartshorne.	Western Coal and Mining Co.	Parting varies between 4 in. and 10 in.
		19, NW. ¼ SW. ¼.		Old working.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	
		19, SE. ¼ SE. ¼.		Drill hole, 36 ft.	Coal, 1 ft. 4 in. Shale, 2 in. Coal, 2 ft. 2 in.	Hartshorne.	Western Coal and Mining Co.	
		19, SW. ¼ SW. ¼.		Old slope.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	
		20, SE. ¼ NE. ¼.		Shaft.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	Not working.
		20, NW. ¼ NE. ¼.	Stiewell.	Old shaft.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	

9	25	20, SE. ¼ SW. ¼.		Drill hole, 27 ft.	Coal, 1 ft. 9 in. Shale, 6 in. Coal, 2 ft.	Hartshorne.	Western Coal and Mining Co.	
		21 NE. ¼ NE. ¼.		Drill hole, 72 ft.	Coal, 2 ft. 6 in. Shale, 4 in. Coal, 8 in.	Hartshorne.	Jollin.	In the N. ½ of sec. 21 are 12 drill holes showing coal.
		21, SE. ¼ NE. ¼.		Drill hole, 29 ft.	Coal, 2 ft. 9 in.			
		29, NW. ¼.		3 shafts.	Coal, 3 ft. 10 in.	Hartshorne.	Citizen.	Small parting near center.
		29, SW. ¼.		Old slopes.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	Coal is in two benches.
		30, NE. ¼.		Shaft.	Coal, 3 ft. 10 in.	Hartshorne.	Citizen.	
		30, SW. ¼.	Black Diamond.	Shaft, 28 ft.	Shale roof. Coal, 2 ft. Parting. Coal, 2 ft. Shale floor.	Hartshorne.	U. S. Geol. Survey.	Coal varies between 3 ft. 6 in. and 4 ft. Parting not always present.
		30, SW. ¼.	Henry West.	Shaft.	Coal.	Hartshorne.	Citizen.	Same as next above.
8	25	12, SE. ¼ SE. ¼.		Drill hole, 567 ft.	Coal, 10 in. Parting, 10 ft. Shaly coal, 2 ft.	Hartshorne.	Arkansas Anthracite Coal Co.	
		9, SE. ¼ SE. ¼.		Drill hole, 502 ft.	Shaly coal, 6 in.	Hartshorne.	Arkansas Anthracite Coal Co.	
		7, SE. ¼ SW. ¼.		Drill hole, 481 ft.	Coal, 10 in.	Hartshorne.	Arkansas Anthracite Coal Co.	
		22, SE. ¼.		Crop.	Coal.	Charleston.	U. S. Geol. Survey.	Blossom in road.

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T. N.	R. W.	Section.						
7	25	8, S. ½.		Crop.	Coal.	Charleston.	U. S. Geol. Survey.	Blossom in road.
		12, NE. ¼ NE. ¼.		Crop.	Coal, 1 ft. 3 in.	Charleston.	U. S. Geol. Survey.	
10	24	9, NE. ¼.		Crop.	Coal, 1 ft. 5 in.	Charleston.	U. S. Geol. Survey.	
		36, E. ½.	McConnell.	Slope.	Coal, 1 ft. 8 in.	Hartshorne.	U. S. Geol. Survey.	Shaft is being sunk near.
		1, NW. ¼.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom in road.
		3, NE. ¼.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom in road.
		5, NW. ¼.		Old working.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	
		6, NE. ¼.		Old working.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	
		7, SE. ¼.		Old working.	Coal, 1 ft. 10 in.	Hartshorne.	U. S. Geol. Survey.	
		8, W. ½.		Old slope.	Coal, 1 ft. 9 in.	Hartshorne.	U. S. Geol. Survey.	
		10, N. ½.		Drill hole, 226 ft.	Coal, 3 ft. 8 in. Parting, 6 in.	Hartshorne.	Citizen.	

9	24	14, SW. ¼.	Pigg and Collier, Eureka Anthracite Coal Co.	Shaft, 140 ft.	Shale roof. Coal, 1 ft. 4 in. Parting, 6 in. Coal, 1 ft. 10 in.	Hartshorne.	U. S. Geol. Survey.	
		17, SW. ¼ NW. ¼.		Old slope.	Coal, 3 ft.	Hartshorne.	U. S. Geol. Survey.	
		18, NW. ¼.		Old working.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	
		19.		Drill hole, 443 ft.	Coal; no record.	Hartshorne.	Citizen.	
		20, N. ½.	Southwestern Coal Co.	Shaft, 315 ft.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	
		20, S. ½.		Drill hole, 483 ft.	Coal; no record.	Hartshorne.	Citizen.	
		21, SW. ¼.		Drill hole, 448 ft.	Coal; no record.	Hartshorne.	Citizen.	
		21, E. ½.		Drill hole, 268 ft.	Coal, no record.	Hartshorne.	Citizen.	
		22, W. ½.	Scranton Anthracite Coal Co.	Shaft, 200 ft.	Coal, 1 ft. 8 in. Parting, 2 in. Coal, 1 ft. 8 in.	Hartshorne.	U. S. Geol. Survey.	
		22, NE. ¼.	Central Anthracite Coal Co.	Shaft, 200 ft.	Coal, 1 ft. 8 in. Parting, 2 ft. Coal, 1 ft. 8 in.	Hartshorne.	U. S. Geol. Survey.	
		23, SE. ¼.	Duck's Nest.	Shaft, 42 ft.	Coal, 2 ft. 10 in. Parting?.	Hartshorne.	Martin Rafter.	
		23, NW. ¼ NW. ¼.	Needmore Mine, Spadra Creek Coal Co.	Shaft, 100 ft.	Shale roof. Coal, 1 ft. 5 in. Parting, 2 in. Coal, 1 ft. 10 in. Sandstone floor.	Hartshorne.	U. S. Geol. Survey.	

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T.N.	R.W.	Section.						
9	24	23, NW. ¼ NW. ¼.	McWilliams, Ward & Co.	Shaft, 85 ft.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	
		23, NE. ¼ NE. ¼.	No. 5, Consolidated Anthracite Coal Co.	Slope.	Shale roof. Coal, 1 ft. 4 in. Parting, 4 in. Coal, 1 ft. 8 in. Sandstone floor.	Hartshorne.	U. S. Geol. Survey.	
		24, NW. ¼ NW. ¼.	Clark and McWilliams.	Shaft, 100 ft.	Coal, 3 ft. 3 in. Parting ?.	Hartshorne.	Martin Rafter.	
		24, NW. ¼ NE. ¼.	No. 1, Consolidated Anthracite Coal Co.	Shaft, 87 ft.	Shale roof. Coal, 1 ft. 4 in. Parting, 4 in. Coal, 1 ft. 8 in.	Hartshorne.	U. S. Geol. Survey.	
		24, NE. ¼ NW. ¼.	No. 3, Consolidated Anthracite Coal Co.	Shaft, 91½ ft.	Shale roof. Coal, 1 ft. 4 in. Parting, 4 in. Coal, 1 ft. 8 in. Sandstone floor.	Hartshorne.	U. S. Geol. Survey.	
		2, SW. ¼ NW. ¼.		Drill hole, 848 ft.	Coal, 3 ft. 6 in. Parting, 4 in.	Hartshorne.	Arkansas Anthracite Coal Co.	
		5, SW. ¼ SE. ¼.		Drill hole.	Coal, 5 ft. 4 in. Parting, 1 in.	Hartshorne.		Thickness of coal includes parting.
		12, NW. ¼ NW. ¼.		Drill hole, 1,137 ft.	Coal, 1 ft. 2 in. Parting, 3½ in. Coal, 1 ft. 8 in.	Hartshorne.	Arkansas Anthracite Coal Co.	

8	24	15, SE. ¼ SW. ¼.		Drill hole, 433 ft.	Coal, 3 ft. 8 in.	Hartshorne.	Arkansas Anthracite Coal Co.	
		17, SE. ¼ SE. ¼.		Drill hole, 670 ft.	Coal, 2 ft. 2 in. Shaly coal, 3 ft. 2 in.	Hartshorne.	Arkansas Anthracite Coal Co.	
		17, NE. ¼ NE. ¼.		Drill hole, 924 ft.	Coal, 1 ft. 4 in.	Hartshorne.	Arkansas Anthracite Coal Co.	
		20, NW. ¼ SE. ¼.		Drill hole, 413 ft.	Coal, 2 ft. 2 in. Shaly coal, 3 ft.	Hartshorne.	Arkansas Anthracite Coal Co.	Coal is shaly at the base.
		21, SW. ¼ SE. ¼.		Drill hole, 86 ft.	Coal, 3 ft.	Hartshorne.	Arkansas Anthracite Coal Co.	
		21, SE. ¼ SE. ¼.		Drill hole, 42 ft.	Coal, 3 ft.	Hartshorne.	Arkansas Anthracite Coal Co.	
		22, NE. ¼ SW. ¼.		Drill hole, 80 ft.	Coal, 3 ft. 4 in.	Hartshorne.	Arkansas Anthracite Coal Co.	
		22, SW. ¼ NE. ¼.		Drill hole, 215 ft.	Coal, 1 ft. 6 in. Shaly coal, 1 ft. 9 in.	Hartshorne.	Arkansas Anthracite Coal Co.	125 ft. below is another bed.
		23, near center.		Shaft, 54 ft.	Coal, 3 ft. 2 in.	Hartshorne.	Citizen.	
		23, NE. ¼.		Drill hole, 278 ft.	Coal, 3 ft.	Hartshorne.	C., R. I. & P. Railroad.	
		24, SE. ¼ NW. ¼.		Drill hole, 65 ft.	Coal, 1 ft. 2 in.	Hartshorne.	Arkansas Anthracite Coal Co.	
		24, SW. ¼ NE. ¼.		Drill hole, 88 ft.	Coal, 11 in.	Hartshorne.		
		24, NE. ¼ NE. ¼.		Drill hole, 403 ft.	Coal.	Hartshorne.	Arkansas Anthracite Coal Co.	"Thin bed."

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T. N.	R. W.	Section.						
8	24	28, NW. ¼ NW. ¼.		Drill hole, 168 ft.	Coal, 2 ft. 10 in.	Hartshorne.	Arkansas Anthracite Coal Co.	
10	23	9, SW. ¼.		Crop.	Coal.	Hartshorne.	Arkansas Anthracite Coal Co.	Blossom.
		10, SW. ¼.		Crop.	Coal, 1 ft. 2 in.	Hartshorne.	Citizen.	
		17, N. ½.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom.
		20, NW. ¼.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom.
		21, SE. ¼.		Crop.	Coal, 1 ft. 3 in.	Hartshorne.	U. S. Geol. Survey.	
		27, SW. ¼ SW. ¼.	Mason.	Slope.	Sandstone roof. Coal, 1 ft. 9 in. Shale floor.	Hartshorne.	E. L. Mason.	
		34, NE. ¼.		Old strip.	Coal, 1 ft. 3 in.	Hartshorne.	Citizen.	
		6, N. ½.		Drill hole.	Coal.	Hartshorne.	Citizen.	Reported at 300 ft. and at 500 ft.
		11, NE. ¼.		Drill hole, 646 ft.	Coal.	Hartshorne.	Garner.	
		11, SW. ¼.		Crop.	Coal, 8 in.	600 ft. above Hartshorne.	U. S. Geol. Survey.	
		14, NW. ¼.		Crop.	Coal, 8 in.		U. S. Geol. Survey.	

9	23	16, SW. ¼.	Union Anthracite Coal Co.	Shaft, 150 ft.	Shale roof. Coal, 3 ft. Parting, 3 in.	Hartshorne.	Higgins.	
		17.	Brooks Mine, Western Anthracite Coal Co.	Shaft, 240 ft.	Shale roof. Coal, 1 ft. 7 in. Shale, 2 in. Coal, 1 ft. 1 in.	Hartshorne.	U. S. Geol. Survey.	
		17.	Clarksville Anthracite Coal Co.	Shaft, 112 ft.	Coal, 3 ft. 6 in. Parting ?.	Hartshorne.	Rafter.	
		18, SE. ¼.		Old workings.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	
		28, SW. ¼ SW. ¼.		Drill hole, 437 ft.	Coal, 3 ft. 10 in. Parting, 4 in.	Hartshorne.	Arkansas Anthracite Coal Co.	
		30, NE. ¼ NE. ¼.		Drill hole, 270 ft.	Coal, 3 ft. 4 in. Parting, 2 in.	Hartshorne.		
		31, NE. ¼ SW. ¼.		Drill hole, 518 ft.	Coal, 1 ft. 7 in. Parting, 4½ in. Coal, 1 ft. 11½ in.	Hartshorne.	Arkansas Anthracite Coal Co.	
8	23	20, NW. ¼ NW. ¼.		Drill hole, 533 ft.	Coal.	Hartshorne.	Arkansas Anthracite Coal Co.	Thin coals at 488 ft. and at 533 ft.
		21, NE. ¼ SE. ¼.		Drill hole, 525 ft.	Coal.	Hartshorne.	Arkansas Anthracite Coal Co.	Thin coal at 525 ft.
		28, SE. ¼ NW. ¼.		Drill hole, 114 ft.	Coal.	Hartshorne.	Arkansas Anthracite Coal Co.	Thin coal at 114 ft.

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T. N.	R. W.	Section.						
7	23	4, W. ½.		Drill hole, 470 ft.	Shaly coal, 1 ft.	Hartshorne.	H. H. Jackman.	Coal at 35 ft.
		4, W. ½.		Drill hole, 470 ft.	Shaly coal, 3 ft.	435 ft. below Hartshorne.	H. H. Jackman.	Coal at 470 ft.; same hole as above.
		6, W. ½.		Drill hole, 584 ft.	Shaly coal, 1 ft.	Hartshorne.	H. H. Jackman.	Coal at 71 ft.
		6, W. ½.		Drill hole, 584 ft.	Coal, 1 ft. Shaly coal, 7 in. Coal, 1 ft. 6 in.	451 ft. below Hartshorne.	H. H. Jackman.	Coal at 522 ft.; same hole as above.
10	22	29, NW. ¼ NW. ¼.	Mose Pearson.	Old working.	Sandstone roof. Coal, 1 ft. 2 in. to 1 ft. 6 in.	Hartshorne.	U. S. Geol. Survey.	
		1, NW. ¼.		Crop.	Coal, 6 in.	Hartshorne sandstone.	U. S. Geol. Survey.	
		5, NW. ¼.		Old working.	Coal, 1 ft. 6 in. to 1 ft. 8 in.	Hartshorne.	Citizen.	
		6, SW. ¼.	Madison mine.	Shaft, 21 ft.	Coal, 1 ft. 8 in. Parting, 7 in. Coal, 8 in.	Hartshorne.	Madison.	
		7, NW. ¼.	Garner.	Shaft.	Coal, 2 ft. 1 in. Parting. Coal, 1 ft.	Hartshorne.	Garner.	

9	22	8, E. ½.		Crop.	Coal, 9 in. Shale, 5 in. Coal, 7 in.	Hartshorne.	U. S. Geol. Survey.	
		9, SW. ¼.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom.
		16, NW. ¼.		Prospect.	Coal, 5 in. Bony coal, 2 ft. 1 in. Sandstone, 5 in. Bone, 1 ft.	Hartshorne.	U. S. Geol. Survey.	
		20, SE. ¼ NE. ¼.		Prospect.	Coal; no record.	Charleston.	U. S. Geol. Survey.	
		25, W. ½.		Prospect.	Coal; no record.	Charleston.	Citizen.	
		30, NE. ¼.		Crop.	Coal, 10 in.	Charleston.	U. S. Geol. Survey.	
8	22	36, S. ½.		Well.	Coal; no record.	Hartshorne.	Citizen.	
9	21	22, SW. ¼.		Crop.	Coal.	About 1,000 ft. below Hartshorne.	U. S. Geol. Survey.	Blossom.
8	21	SE. part of township.			Coal.		Citizen.	Reported on Joe Loss's place.
		15, SW. ¼.		Well.	Coal; no record.	About 1,000 ft. below Hartshorne.	Citizen.	
6	21	27, NW. ¼.		Well.	Coal; no record.	About 1,000 ft. below Hartshorne.	Citizen.	
		33, SE. ¼.		Well.	Coal; no record.	About 1,000 ft. below Hartshorne.	Citizen.	

Table of mines, openings, and exposures of coal—Continued.

Location.			Name of opening.	Kind of exposure.	Section of coal bed.	Stratigraphic horizon.	Examined or reported by—	Remarks.
T. N.	R. W.	Section.						
6	21	34, E. ½.		Crop.	Coal, 1 ft. 6 in. to 1 ft. 8 in.	About 1,000 ft. below Hartshorne.	U. S. Geol. Survey.	
		35, NW. ¼ NW. ¼.		Drill hole, 300 ft.	Coal, 8 in. Shale, 2 in. Coal, 1 ft. 8 in.	About 1,000 ft. below Hartshorne.	Citizen.	
		35, W. ½.		Drill hole, 80 ft.	Coal, 8 in. Shale, 2 in. Coal, 1 ft. 8 in.	About 1,000 ft. below Hartshorne.	Citizen.	
8	20	20 SW. ¼.		Old drift.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	
		28, NW. ¼.	Humphrey-Smith Coal Co.	Shaft, 38 ft.	Shale roof. Coal, 2 ft. 4 in.	Hartshorne.	Humphrey.	
		29 NW. ¼.		Prospect.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	
		30.		15 or 20 openings.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	Coal is shallow.
		30 SW. ¼.	Ouita Coal Co.	Shaft.	Coal, 2 ft. 2 in.	Hartshorne.	U. S. Geol. Survey.	
		17, SW. ¼.		Old shaft, 60 ft.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	
		18, SE. ¼.		Old slope.	Coal; no record.	Hartshorne.	U. S. Geol. Survey.	

7	20	21, N. ½.	Southern Anthracite Coal Co.	Slope.	Shale roof. Coal, 8 in. to 10 in. Parting, 6 in. to 10 in. Coal, 1 ft. 10 in. to 2 ft. 2 in. Sandstone floor.	Hartshorne.	U. S. Geol. Survey.	
		21, SW. ¼ NE. ¼.	Southern Anthracite Coal Co.	Shaft, 480 ft.	Section same as next above.	Hartshorne.	U. S. Geol. Survey.	
		22, NW. ¼.	Russellville Anthracite Coal Co.	Shaft, 70 ft.	Shale roof. Coal, 8 in. to 10 in. Parting, 6 in. to 10 in. Coal, 1 ft. 10 in. to 2 ft. 2 in. Sandstone floor.	Hartshorne.	U. S. Geol. Survey.	
		22, E. ½.	Russellville Anthracite Coal Co.	Slope.	Same section as next above.	Hartshorne.		
		25, SE. ¼.		Old shaft.	Coal; no record.	Below Hartshorne.	Citizen.	
		27, SW. ¼.		Crop.	Coal.		Citizen.	Blossom.
		28, NE. ¼.		Crop.	Coal.	Hartshorne.	U. S. Geol. Survey.	Blossom.
		29, SE. ¼.		Crop.	Coal.	Below Hartshorne.	Citizen.	Blossom.
		35, SW. ¼.		Crop.	Coal.		Citizen.	Blossom.
		36, SW. ¼.		Prospect.	Coal, 1 ft.	Below Hartshorne.	U. S. Geol. Survey.	

INDEX.

A. Page.

- Acknowledgments to those aiding 2-4
- Aclis stevensana, occurrence of 34
- Alabama coals, boiler tests of 103
- Alethopteris ambigua, occurrence of 31
  - seslii, occurrence of 25, 26, 27, 29, 30, 31
    - var. missouriensis, occurrence of 29
- Allerisma terminale, occurrence of 34
- Alma, coal near 65, 68, 77, 79, 83
  - coal near, analysis of 88
- Alma district. *See* Van Buren and Alma district.
- Aloiopteris winslovii, occurrence of 27, 29
- Alston, coal near, analysis of 88
- Altus, coal near 66, 83
  - coal near, analysis of 98
    - description of 94
  - fossils near 29
- Altus fault, description of 45
- Androstachys sp., occurrence of 28
- Annularia radiata, occurrence of 25, 30
  - sphenophylloides, occurrence of 25, 26, 27, 29, 30, 31
  - stellata, occurrence of 26, 31
  - sp., occurrence of 27
- Anticlines, description of 37-39
- Aphlebia hirsuta, occurrence of 25, 27, 30
- Area of region 4-5
- Arkansas coal No. 1, analyses of 96
  - boiler tests of 103
  - coking tests of 99
  - description of 89
  - No. 1 A, analysis of 96
    - description of 89
  - No. 1 B, analysis of 96
    - description of 89
  - No. 1 C, analysis of 96
    - description of 89
  - No. 2, analyses of 99
    - boiler tests of 103
    - coking tests of 99
    - description of 89
  - No. 2 A analysis of 97
    - description of 89
  - No. 2 B analysis of 97
    - description of 89
  - No. 2 C, analysis of 97
    - description of 89
  - No. 3, analysis of 97
    - boiler tests of 103
    - description of 89
  - No. 3 A, analysis of 97
    - description of 89-90

Page

- Arkansas coal No. 3 B, analysis of 97
    - description of 90
  - No. 3 C, analysis of 97
    - description of 90
  - No. 4, description of 90
  - No. 5, description of 90
  - No. 5 A, analysis of 98
    - description of 90
  - No. B analysis of 98
    - description of 90
  - No. 5 C, analysis of 98
    - description of 90
  - No. 6, analysis of 97
    - description of 90
- Arkansas Geological Survey, analyses by 87-88
- Arkansas River, description of 8
  - flood plains of 22
- Arkansas Valley, description of 9-10
  - faults in 36
  - structure of 36
- Artesian wells, failure of 47
- Asolanus camptotænia, occurrence of 26
- Astartella concentrica, occurrence of 33, 34
  - vera, occurrence of 32
  - varica, occurrence of 32, 33, 34
  - sp., occurrence of 33
- Asterophyllites equisetiformis, occurrence of 28, 30
- Atkins, coal near 82
- Atoka formation, coals in 81-83
  - correlation of 12
  - fossils in 15
  - gas in 15
  - occurrence and character of 11, 13-15, 38, 45
  - sections of, figures showing 14
  - structure in, plate showing 20
- Auburn, coal at 59, 65, 78
  - coal at, analysis of 98
    - section of, figure showing 20
  - section at, figure showing 20
- Avicula acosta, occurrence of 33
- Aviculipecten coxanus, occurrence of 34
  - germanus, occurrence of 34
  - whitei, occurrence of 31, 32, 33
  - sp., occurrence of 32, 33
- Aviculipinna americana, occurrence of 34

B.

- Backbone Ridge, coal in and near 51, 56, 57, 81
  - geology of 14, 51-52
- Backbone Ridge fault, description of 41
  - section of, figure showing 41

Page.

Backbone syncline, description of 37
Bates, coal near 62
  coal near, analyses of 96
    description of 95
Bates and Coaldale district, coal of 62-63
  coal of, analyses of 96
    calorific value of, figure showing 87
    composition of, figure showing 85
    description of 95
    sections of, figure showing 63
Bellerophon harrodi, occurrence of 34
  sp., occurrence of 33
Big Creek, coal at 78
  coal at, section of, figure showing 77
Big Danger fault, description of 43
Big Danger Hill, coal at 70, 71
  geology of 19, 43
Biswell Hill, geology near 52
Biswell Hill anticline, description of 37-38
Bloomer, geology near 19
Boggy shale, correlation of 12
  occurrence and character of 11
Boiler tests, description and results of 101-103
Bonanza, coal at and near 51-54
  coal at and near, analyses of 97
    boiler tests of 103
    coking of 99
    section at, figure showing 54
  geology at 12, 15
Bonanza and Jenny Lind district, coals of 51-55, 78-79
  coals of, analyses of 97-98
    calorific value of, figure showing 87
    composition of, figure showing 85
    sections of, figures showing 54, 55
Booneville, coal near 81
  coal near analysis of 88
Boston Mountains, description of 9
  structure of 35-36
Brackett, R. N., analyses by 88
Branch, coal near 64
Branner, J. C., work of 2
Briquetting tests, description of 100-101
Burma, coal near 17, 57, 61
  coal near, analyses of 96
    calorific value of, figure showing 87
    composition of, figure showing 85
    description of 91-92
    sections of, figure showing 60
  fossils near 26, 33
  geology at and near 16, 17, 57
Burrows, J. S., sampling by 90

C.

Cabin Creek, building stone at 20
  coal near 80
  geology near 70
  sandstone jointing near, view of 20
Cabin Creek syncline, description of 40
Calamites ramosus, occurrence of 29
  suckowii, occurrence of 28
  sp. occ rrence of 29
Calamostachys sp., occurrence of 25
Callipteridium inæquale, occurrence of 30
  membranaceum occurrence of 27
  sullivantii. occurrence of 30, 31

Page.

Campbell, M. R., on formation of folds 45
  on natural mounds 22-23
  sampling by 90
  work of 2
Carboniferous rocks, occurrence and character of 11-22
Cardiocarpon bicuspidatum, occurrence of 25
  branneri, occurrence of 31
  circulare, occurrence of 26, 31
Catholic Hill, geology at 45
Caulksville, coal near 64, 65, 77, 78
  fossils near 27, 31
Caulksville fault, description of 42
Center Cross, coal at, description of 94
Central, coal at 58, 77, 78
  coal at, analysis of 88
    section of, figure showing 77
Central syncline, description of 39
Charleston, coal near 63-64, 77-78, 80
  coal near, description of 92-93
    sections of, figure showing 77
  fossils near 28
  geology near 20
Charleston and Paris district, coal of 63-65
  coal of, calorific value of, figure showing 87
Charleston coal, character and description of 77-80, 92-93
  composition of, figure showing 85
  description of, name of 49
  fossils of 27-28
  occurrence of 65-66
  openings on 117, 119, 130-134, 137, 140, 147
  samples of, description of 92-93
  sections of 119, 130, 137
    figure showing 77
  See also Coal Ridge coal.
Charleston district, coals of 77-78
  coals of, analysis of 98
    description of 92-93
Cheilanthites pluckenetti, occurrence of 30
  squamosus, occurrence of 25, 26, 29, 30
  trifoliatus, occurrence of 25, 28
Chickalah, coal near 82
Chismville, section at, figure showing 16
Clarksville, coal near 70, 72
  coal near, analysis of 88
    description of 93
  geology near 19, 70
Clarksville fault, description of 42-43
  section of, figure showing 43
Classification of coals 84-86
Coal, analyses of 87-99
  character of 83-87
  classification of 84-86
  composition of, figure showing 85
  developments of 112-149
  distribution of 49-93
  efficiency of 86-87
  mining of, methods of 105-106
  openings on 112-149
  preparation of 106-107
  production of 103-105
  tests of 99-103
Coal-bearing rocks, age of 24
  columnar section of, plate showing 12
  deposition of 24

Page.
Coal-bearing rocks, occurrence and character of........ 12-13
section of........ 13
Coal beds, description of........ 50-83
development of........ 103-112
distribution of........ 49-50
formation of........ 49
geologic position of........ 4-5
mines and openings on........ 112-149
minor structure of, figure showing........ 48
openings on........ 112-149
sections of........ 113-149
thickness of........ 106
Coal Hill, coal near........ 68
coal near, analysis of........ 88, 98
boiler tests of........ 103
description of........ 93-94
See also Arkansas coal, No. 5.
fossils near........ 25, 26
structure of........ 66
Coal Hill and Denning district, coal of........ 65, 66-86
coal of, analyses of........ 98
briquettes of........ 101
calorific value of, figure showing........ 87
character of........ 86
composition of, figure showing........ 85
sections of, figure showing........ 68
fault in........ 65
map of........ 67
structure of, figure showing........ 67
Coal Hill anticline, description of........ 39, 66
Coal Hill coal, correlation of........ 24
fossils of........ 25-26
Coal Hill district, coal of........ 65, 82
Coal Hill fault, description of........ 45
Coal Ridge, coal at........ 78
coal at, section of, figure showing........ 77
geology at........ 78
Coal Ridge coal, character and distribution of........ 77-80
correlation of........ 24
fossils of........ 24, 27
See also Charleston coal.
Coaldale, coal near........ 63
fossils from........ 33
Coaldale district. *See* Bates and Coaldale district.
Coking tests, results of........ 99-100
Collier, A. J., fossils collected by........ 24
sampling by........ 91, 94
Columnar section, plate showing........ 12
Commercial relations, account of........ 7-8
Composita subtilita, occurrence of........ 32, 33, 34
Coops Prairie, gas at........ 38
Cordaianthus fluitans, occurrence of........ 30
ovatus, occurrence of........ 31
Cordaites communis, occurrence of........ 27
principalis, occurrence of........ 30
sp., occurrence of........ 30
Correlation, details of........ 10-13
Crania sp., occurrence of........ 32
Crinoidal fragments, occurrence of........ 32, 33, 34
Crossotheca ophioglassoides, occurrence of. 29, 30
Cypricardinia carbonaria, occurrence of........ 34

D. Page.
Dardanelle, coal near........ 82, 83
section at, figure showing........ 14
Deltopecten occidentalis, occurrence of.. 32, 33, 34
texanum, occurrence of........ 33
Denning, coal near........ 83
coal near, analyses of........ 88, 98
character of........ 68
description of........ 90
See also Arkansas coal No. 4.
fossils near........ 26
sections at, figures showing........ 14, 16, 68
Denning coal. *See* Arkansas coal No. 5.
Denning district. *See* Coal Hill and Denning district.
Derbya crassa, occurrence of........ 33, 34
sp., occurrence of........ 32, 33
Development, conditions of........ 103-112
Devils Backbone Ridge, coal in........ 56, 59, 64
geology at........ 15, 16
Devils Backbone Ridge fault, description of 42
Dicks Branch, coal on........ 76
Dielasma bovidens, occurrence of........ 34
sp., occurrence of........ 32, 33
Dolerophyllum angularis, occurrence of........ 25
Drainage, description of........ 8-9
Drainage, mine, methods of........ 106

E.
Economic geology, description of........ 49-149
Edmondia mortonana, occurrence of........ 34
nebraskensis, occurrence of........ 32
subtruncata, occurrence of........ 32
sp., occurrence of........ 32
Elevations, description of........ 9-10
Ellsworth, coal near........ 82
Eremopteris lincolniana, occurrence of........ 27
spinosa, occurrence of........ 27
Euconospira sp., occurrence of........ 34
Euomphalus catilloides, occurrence of........ 33
Euphemus nodicarinatus, occurrence of........ 32, 33
Excelsior, coal near........ 58, 59
Explosions, rarity of........ 106

F.
Fairchild, H. L., and White, David, fossils determined by........ 23
Faults:
local use of term of........ 40
loss of vein through........ 41
occurrence and description of........ 35-36, 40-41
types of........ 35-36, 40-47
Fidelity Fuel Co., mine of, syncline in, figure showing........ 48
Fistulipora sp., occurrence of........ 33, 34
Fletcher Creek, coal on........ 81
Folds, miniature, description of........ 48-49
figure showing........ 48
Formations, correlation of........ 10-13
description of........ 13-23
Fort Smith, artesian wells at, failure of........ 47
building store at........ 20
coal at and near........ 55, 77, 79
analysis of........ 98
section of, figure showing........ 20

Page.

Fort Smith, gas at ... 15
  geology at ... 19
  fossils near ... 33
  population and situation of ... 7
  section at, figure showing ... 20
Fort Smith coal, openings on ... 113, 119, 127, 130
  sections of ... 113, 119
Fort Smith formation, building stone from ... 20
  coals in ... 19, 77
    sections of, figures showing ... 20
  correlation of ... 12
  fossils in ... 20
  occurrence and description of ... 13, 18–20, 46
  sections of, figure showing ... 20
Fort Smith syncline, description of ... 39
Frazer, Persiflor, on coal classification ... 85
Fuel-testing plant, coal samples of ... 88–95
  coal samples of, analyses of ... 95–99
    boiler tests of ... 101–103
    briquetting tests of ... 100–101
    coking tests of ... 19, 100

G.

Galla Rock, coal near ... 82
Game Hill anticline, description of ... 38
Gas, occurrence of ... 38
Geography, description of ... 4–10
Geologic map and section ... Pocket
Geology, description of ... 10–49
  See also Paleontology; Stratigraphy; Structure.
Geology, economic, description of ... 49–149
Girty, G. H., fossils determined by ... 23
  report of, on Arkansas fossils ... 31–35
Grand Prairie, coal on ... 64
Grand Ridge, geology at ... 78
Greenwood, coals at and near ... 39, 59–60
  coals at and near, analyses of ... 88, 97
    calorific value of, figure showing ... 87
    composition of, figure showing ... 85
    description of ... 92
  geology near ... 19, 52
Greenwood and Huntington district, coal of ... 56–62
  coal of, analyses of ... 96–97
    character of ... 56–57
    depths to ... 62
    distribution of ... 57–62
    location and extent of ... 56
    sections of, figure showing ... 58
Greenwood syncline, coal in ... 56
  description of ... 39
Griffithides sp., occurrence of ... 33
Groves, J. W., sampling by ... 89–90

H.

Hackett, coals at and near ... 39, 56–59, 81
  coals at and near, analyses of ... 88, 97
    calorific value of, figure showing ... 87
    composition of, figure showing ... 85
    description of ... 92
    sections of, figure showing ... 58
  geology at ... 12, 15, 52
  section at, figure showing ... 16

Page.

Hartford, coal near ... 56, 61–62
  coal near, analyses of ... 88, 96
  description of ... 96
  fossils near ... 29
Hartford anticline, description of ... 38
Hartman, coal near ... 67
  fossils near ... 27
Hartman fault, description of ... 44–45
Hartshorne coals, character and distribution of ... 50–51, 57, 89–93
  description of ... 51–77, 89–92
  distribution of, map showing ... 51
  name of ... 49
  occurrence of ... 11, 16–17, 38–39
  openings on ... 113–131, 133–136, 138–149
  sections of ... 113–129, 134–136, 138–149
Hartshorne sandstone, correlation of ... 12
  exposure of, views of ... 16, 18
  occurrence and character of ... 11–13, 15–17, 37–38, 42–46, 50–51, 57, 66, 74, 76–77
  sections of, figures showing ... 16
  structure in, view of ... 18
Haulage, methods of ... 106
Hawlea cristata, occurrence of ... 27
Huntington, coal at and near ... 56, 61–62, 79
  coal at and near, analysis of ... 88
    boiler tests of ... 103
    briquetting of ... 100
    calorific value of, figure showing ... 87
    coking of ... 99
    composition of, figure showing ... 85
    sections of, figure showing ... 61
  gas at ... 15
  section near, figure showing ... 14
Huntington coal, calorific value of, figure showing ... 87
  composition of, figure showing ... 85
  description of ... 89
  occurrence of ... 12
  See also Arkansas coal No. 1.
Huntington district. *See* Greenwood and Huntington district.
Hustedia mormoni, occurrence of ... 32, 33, 34

I.

Illinois coals, boiler tests of ... 103
  briquetting tests of ... 101
Indian Territory, coal-bearing rocks in ... 16
  coal-bearing rocks in, description of ... 11
    section of ... 11
  coals of, boiler tests of ... 103
Investigation of field, need of ... 1
  prosecution of ... 1–4

J.

Jenny Lind, coal at and near ... 52–55
  coal at and near, analyses of ... 88, 97–98
    boiler tests of ... 103
    briquetting of ... 100
    coking of ... 99
    description of ... 89–90, 92
    sections of, figures showing ... 52, 53, 54, 55
    See also Arkansas Nos. 2, 3, 6.

Page.
enny Lind, sections at and near, figures showing 14. 16, 52, 53
enny Lind coal. *See* Arkansas coal No. 3.
enny Lind district. *See* Bonanza and Jenny Lind district.
oints, description of 47–48

K.

Kansas coals, boiler tests of 103

L.

Labor, conditions governing 107–112
Lamar, building stone at 20
  coal at ....
    sections of, figures showing 20, 71
  section at, figure showing 20
  See also Cabin Creek.
Leda bellistriata, occurrence of 34
  nasuta, occurrence of 32, 33
  sp., occurrence of 32, 33
Lepidocystis vesicularis, occurrence of 27
Lepidodendron oblongifolium, occurrence of 29
  sp., occurrence of 29
Lepidophloios scoticus, occurrence of 26
Lepidophyllum lanceolatum, occurrence of 27, 28
  missouriense, occurrence of 26
  ovatifolium, occurrence of 27
Lepidostrobus sp., occurrence of 28
Lima retifera, occurrence of 33, 34
Lingulidiscina convera, occurrence of 34
Linopteris münsteri, occurrence of 27, 28, 31
  squarrosa, occurrence of 25, 27
Little Piney Creek, fossils from 32
Little Short Mountain, geology at 21
Little Vache Grasse Creek, coal at 79
Location, description of 4
London basin, coal in 74
  description of 40
Long Prairie, coal at 52
  section at, figure showing 52
Lophophyllum profundum, occurrence of 32, 33, 34
Loxonema sp., occurrence of 33

M.

McAlester coal, recurrence of 11
McAlester group, coals in 11
  correlation of 12
  occurrence and character of 11, 13
Macrodon obsoletus, occurrence of 32, 33
Magazine Mountain, coal at and near 76, 81
  geology at 20, 21
Mansfield, gas near 15
  geology at 14
Map of Arkansas coal field 5, 6
  of Arkansas coal field, description of 5–7
  of Hartshorne coal 51
Map, structure, of Arkansas coal field 36
Map and sections, geologic, of Arkansas field .... Pocket.
Marginifera ingrata, occurrence of 33, 34
  muricata, occurrence of 32, 33
  sp., occurrence of 33
Mariopteris incompleta, occurrence of 26, 29, 30, 31

Page.
Mariopteris latifolia, occurrence of 25
  muricata, occurrence of 26
  nervosa, occurrence of 25, 26, 29, 30
  occidentalis, occurrence of 25, 26, 29, 30, 31
  sphenopteroides, occurrence of 27, 29, 30, 31
  sp., occurrence of 27, 31
Market, preparation of coal for 106
Mason coal, correlation of 72
Massard fault, description of 46
Massard Prairie, coal at 52, 55
  coal at, description of 94
    section at, figure showing 52
  geology at 16, 52
  sections at and near, figures showing 14, 52
Massard Prairie anticline, description of 38
  gas in 38
Mesler, R. D., sampling by 93–94
  work of 1–2
Michelinia sp., occurrence of 33
Midland, coal near 57, 61
  coal near, analyses of 96
    calorific value of, figure showing 87
    composition of, figure showing 85
    description of 90
    sections of, figure showing 60
Mill Creek fault, description of 45–46
Mill Creek Ridge anticline, coal on 64
  description of 38
Mines, abandonment of, owing to faulting 41
  list of 113–149
Mining, conditions of 103–112
  methods of 105–106
Minnow Creek, coal on 76
Mississippian rocks, occurrence and character of 11
Missouri coals, boiler tests of 103
Modiola subelliptica, occurrence of 33
Monilipora sp., occurrence of 33
Montana, coal near 71
Montreal, coal near 17, 56, 57, 60
  coal near, analysis of 97
    calorific value of, figure showing 87
    composition of, figure showing 85
    description of 91
    sections of, figure showing 60
  geology near 57
Montreal syncline, description of 38
Moores Rock, coal at 79
Mounds, natural, occurrence and explanation of 23
Mulberry, coal near 65
Mulberry fault 46–47
Mulberry Mountain, coal at 80
Murchisonia sp., occurrence of 32
Myalina aviculoides, occurrence of 34
  perattenuata, occurrence of 34
  perniformis, occurrence of 32, 34

N.

Naticopsis nana, occurrence of 32
  sp., occurrence of 32
Nautilus sp., occurrence of 32, 33, 34
Nebo Mountain, coal near 82
  geology at 76–77
Neuropteris capitata, occurrence of 25, 26, 27
  clarksoni, occurrence of 29, 30

Page.

- Neuropteris fimbriata, occurrence of 30
  - harrisi, occurrence of 25, 26
  - jenneyi, occurrence of 27
  - missouriensis, occurrence of 25, 26, 27, 29, 30, 31
  - ovata, occurrence of 26, 27, 29, 30
  - rarinervis, occurrence of 27, 29, 30
  - rogersii, occurrence of 25
  - scheuchzeri, occurrence of 25, 26, 27, 28, 29, 30, 31
  - tenuifolia, occurrence of 25, 26
- Nucula ventricosa, occurrence of 32, 33

O.

- Oak Valley, coal near 53
  - analysis of 88
- Odontopteris bradleyi, occurrence of 29, 30
- Orthoceras cribrosum, occurrence of 34
  - sp., occurrence of 32
- Ostracoda sp., occurrence of 32
- Ouachita Mountains, description of 10
  - structure of 35
- Ouita basin, coal in 74-75
  - coal in, section of, figure showing 16
  - description of 40, 74-75
  - section in, figure showing 16
- Ozark, coal near 83
  - coal near, analyses of 88
    - section of, figure showing 77
  - geology near 83

P.

- Pachypteris gracillima, occurrence of 29
- Paige, Sidney, sampling by 92
  - work of 1
- Paleontology, conclusions from 23–24
  - description of 23–35
- Parallelodon tenuistriatus, occurrence of 34
- Paris, coal at and near 40, 63, 80
  - coal at and near, analyses of 88, 98
    - description of 93
  - fossils near 28, 33
  - geology at and near 20, 21
- Paris coal, age of 24
  - calorific value of, figure showing 87
  - character and distribution of 80–81
  - composition of, figure showing 85
  - correlation of 49
  - description of 93
  - fossils of 28
  - occurrence of 21
  - openings on 136–137
  - sections of 136–137
- Paris district, coal of 79
  - coal of analysis of 98
    - character of 86
    - description of 93
  - *See also* Charleston and Paris district.
- Paris shale, correlation of 12
  - fossils of 21
  - occurrence and character of 13, 20–21
  - sections of, figure showing 21
- Paris syncline, description of 40
- Patellostium marcouanum, occurrence of 34
  - sp., occurrence of 32
- Pecopteris candolliana, occurrence of 27, 29
  - clintoni, occurrence of 26

Page.

- Pecopteris dentata, occurrence of 29, 30
  - emarginata, occurrence of 26
  - jenneyi, occurrence of 29
  - oreopteridia, occurrence of 27, 31
  - (Scolecopteris) miltoni, occurrence of 25, 27
  - plumosa, occurrence of 25
  - robusta, occurrence of 26, 30, 31
  - vestita, occurrence of 25-30, 31
  - villosa, occurrence of 27, 29, 30
  - sp., occurrence of 25
- Pennsylvanian rocks, occurrence and character of 11-22
- Personnel of investigation 1-2
- Petit Jean Mountain, geology at 76-77
- Phillipsia cliftonensis, occurrence of 34
- Philpott coal, correlation of 50, 92
- Philpott district, coal of 75-76, 80
  - coal at, section of 76
- Phyllotheca sp., occurrence of 26
- Pickartz coal, correlation of 50, 76
  - description of 76
- Pine Ridge, coal on 64
- Pine Ridge fault, description of 42
- Piney Creek, coal near 72
  - sandstone near, view of 18
- Platyceras nebraskense, occurrence of 32
- Pleasant Hill, fossils near 29
- Pleurophorus angulatus, occurrence of 32
  - immaturus, occurrence of 32, 34
  - oblongus, occurrence of 32
  - subcostatus, occurrence of 31, 32, 33
  - tropidophorus, occurrence of 34
  - sp., occurrence of 34
- Pleurotomaria brazoensis, occurrence of 33
  - giffordi, occurrence of 34
  - subconstricta, occurrence of 34
  - tenuicincta, occurrence of 34
  - sp., occurrence of 32
- Plymouth, fossils from 33
- Polypora sp., occurrence of 33
- Potato Hill, coal at and near 39, 64, 81
  - geology at 20, 21
  - section at, figure showing 21
  - view of 16
- Poteau Mountain, coal near 57, 62–63, 79, 81
  - coal near, character of 86
    - description of 94
    - sections of, figure showing 63
  - fossils from 34, 35
  - geology at 12, 20, 22
- Poteau River, description of 8–9
- Poteau syncline, description of 39–40
- Prairie View, coal at and near 65, 72
  - coal at and near, analysis of 88
    - section of, figure showing 20
  - section at, figure showing 20
- Prairie View anticline, description of 38–39
- Prairie View district, coal of 72–74, 79
  - coal of, sections of, figure showing 73
  - structure of, figure showing 69
- Prairie View fault, description of 42
- Prairie View syncline, description of 40
- Prismopora sp., occurrence of 32
- Production, statistics of 103–105
- Productus cora, occurrence of 34
  - nebraskensis, occurrence of 34

Page.

- Productus, sp., occurrence of 32
- Pseudomonotis sp., occurrence of 34
- Pseudopecopteris macilenta, occurrence of 25,27
- Pteria ohioensis, occurrence of 33,34
- Pugnax osagensis, occurrence of 34
- Purdue, A. H., fault determined by 42
  - on Arkansas coal field 12
  - work of 2,3

R.

- Railroads, description of 8
- Renaultia sp., occurrence of 27
- Rhabdocarpus sulcatus, occurrence of 25,26
  - sp., occurrence of 26,30
- Rhombopora lepidodendroides, occurrence of 34
  - sp., occurrence of 32,33
- Rich Mountain, coal at 82
- Rolls, figure showing 53
  - occurrence and character of 49
- Russellville, coal near 74-75,76,83
  - coal near, analysis of 88,99
    - description of 93
  - fossils near 25
  - geology at 16
- Russellville anticline, description of 39
- Russellville district, coal of 74-75
  - coal of, analyes of 99
    - calorific value of, figure showing 87
    - composition of, figure showing 85

S.

- Sallisaw quadrangle, fossils from 31
- Samples, description of 89-95
  - taking of, method of 89
- Savanna formation, coal in 11,22
  - correlation of 12
  - occurrence and character of 11,13,21-22
- Schizodus affinis, occurrence of 34
  - compressus, occurrence of 34
  - sp., occurrence of 32,33
- Scolecopteris miltoni 25
- Scranton Anthracite Co., breaker of, view of 106
- Septopora biserialis, occurrence of 34
- Shinn basin, coal in 74-75,82
  - coal in, description of 93
    - section of, figure showing 16
  - description of 40,75
  - section in, figure showing 16
- Shoal Creek, coal near 82
- Short Mountain, geology at 21
  - section at, figure showing 21
- Sigillaria discophora, occurrence of 28
- Sigillariostrobus quadrangularis, occurrence of 25,26,27
- Sixmile, fossils from 32,34-35
- Sixmile Creek, fossils from 31
- Slack, use of 107
- Smith, Carl P., sampling by 91-95
  - work of 1,2
- Smith, J. P., analyses by 88
  - fossils determined by 23
- Soleniscus klipparti, occurrence of 32

Page.

- Solenomya sp., occurrence of 34
- Spadra, coal near 70-72
  - coal near, analyses of 88,99
    - description of 93,94
  - fossils from 31
  - geology near 70
  - section of 137
- Spadra coal, calorific value of, figure showing 87
  - composition of, figure showing 85
  - description of 93,94
  - occurrence and character of 70,72
- Spadra district, coal of 68-72,80
  - coal of, analyses of 99
    - sections of, figure showing 71
  - faults in 70
  - structure of 69-70
    - figure showing 69
- Spadra fault, description of 44,70
- Spadra shale, coals in 17
  - coals in, sections of, figures showing 18
  - correlation of 12
  - fossils of 18,26-27
  - name of 18
  - occurrence and character of 13,17-18,45
  - sections of, figures showing 18
- Sphaerodoma sp., occurrence of 34
- Sphenophyllum emarginatum, occurrence of 25,26,27,29,30,31
  - emarginatum var. minor, occurrence of 25,27,29
  - fasciculatum, occurrence of 27,29,30,31
  - majus, occurrence of 26,27,29
  - suspectum, occurrence of 25,26
  - thorii, occurrence of 31
- Sphenopteris (Hawlea) cristata, occurrence of 27,81
  - illinoisensis, occurrence of 27
  - mixta, occurrence of 30,31
  - pinnatifida, occurrence of 29,31
  - sp., occurrence of 26,27,28,29
- Spielville, building stone at 20
- Spirifer cameratus, occurrence of 33,34
  - rockymontanus, occurrence of 32,33,34
  - sp., occurrence of 33
- Spiriferina kentuckyensis, occurrence of 33
- Spring Mountain, coal near 82
  - geology at 76-77
- Squamularia perplexa, occurrence of 32
- Stenopora sp., occurrence of 34
- Stratigraphy, correlation of 10-13
  - description of 13-23
- Structure, description of 35-49
  - map showing 36
  - topography and, relation of, figure showing 52
- Sub Rosa, coal near 64
- Sugarloaf Mountain, coal at 57,79,81
  - geology at 20,22
- Sugarloaf syncline, coal at 39
  - description of 39
- Surficial deposits, character of 22-23
- Synclines, coal in 36
  - description of 39-40

T.

Page.

Taff, J. A., fault located by 41
  on Arkansas coal field 12
  work of 3
Tennessee Ridge, geology of 19
Tennessee sandstone, correlation of 19
Topography, description of 9-10
  structure and, relation of 52
Towns, list of 8

U.

Unions, labor, contracts with 107-112

V.

Vache Grasse Creek, coal in 59
Van Buren, coal near 66, 79, 83
  fossils near 32
Van Buren, section near, figure showing 14
Van Buren and Alma district, coal of 65-66, 79
Van Buren coal, fossils of 30

Page.

Ventilation, methods of 106
Vesta, coal at 64

W.

Washing, use of 107
West Virginia coals, boiler tests of 108
White, David, fossils determined by 23
  report of, on Arkansas fossils 24-31
White, David, and Fairchild, H. L., fossils determined by 23
Whiteoak Mountain, coal near 62-63
Winslow, Arthur, work of 2
Winslow formation, correlation of 12
  occurrence and character of 11, 47, 65, 83
  structure in, plate showing 20
Witteville, Ind. T., fossils from 30
Witteville coal, occurrence, of 11

Y.

Yoldia carbonaria, occurrence of 32

CLASSIFICATION OF THE PUBLICATIONS OF THE UNITED STATES GEOLOGICAL SURVEY.

[Bulletin No. 326.]

The publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of United States—folios and separate sheets thereof, (8) Geologic Atlas of the United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists can be had on application.

Most of the above publications can be obtained or consulted in the following ways:

1. A limited number are delivered to the Director of the Survey, from whom they can be obtained, free of charge (except classes 2, 7, and 8), on application.

2. A certain number are delivered to Senators and Representatives in Congress for distribution.

3. Other copies are deposited with the Superintendent of Documents, Washington, D. C., from whom they can be had at prices slightly above cost.

4. Copies of all Government publications are furnished to the principal public libraries in the large cities throughout the United States, where they can be consulted by those interested.

The Professional Papers, Bulletins, and Water-Supply Papers treat of a variety of subjects, and the total number issued is large. They have therefore been classified into the following series: A, Economic geology; B, Descriptive geology; C, Systematic geology and paleontology; D, Petrography and mineralogy; E, Chemistry and physics; F, Geography; G, Miscellaneous; H, Forestry; I, Irrigation; J, Water storage; K, Pumping water; L, Quality of Water; M, General hydrographic investigations; N, Water power; O, Underground waters; P, Hydrographic progress reports; Q, Fuels; R, Structural materials. This paper is the one hundred and fourth in Series A and the one hundred and twenty-eighth in Series B, the complete lists of which follow (PP=Professional Paper; B=Bulletin; WS=Water-Supply Paper):

SERIES A, ECONOMIC GEOLOGY.

B 21. Lignites of Great Sioux Reservation: Report on region between Grand and Moreau rivers, Dakota, by Bailey Willis. 1885. 16 pp., 5 pls. (Out of stock.)

B 46. Nature and origin of deposits of phosphate of lime, by R. A. F. Penrose, jr., with introduction by N. S. Shaler. 1888. 143 pp. (Out of stock.)

B 63. Stratigraphy of the bituminous coal field of Pennsylvania, Ohio, and West Virginia, by I. C. White. 1891. 212 pp., 11 pls. (Out of stock.)

B 111. Geology of Big Stone Gap coal field of Virginia and Kentucky, by M. R. Campbell. 1893. 106 pp., 6 pls. (Out of stock.)

B 132. The disseminated lead ores of southeastern Missouri, by Arthur Winslow. 1896. 31 pp. (Out of stock.)

B 138. Artesian-well prospects in Atlantic Coastal Plain region, by N. H. Darton. 1896. 228 pp. 19 pls.

B 139. Geology of Castle Mountain mining district, Montana. by W. H. Weed and L. V. Pirsson. 1896. 164 pp., 17 pls.

B 143. Bibliography of clays and the ceramic arts, by J. C. Branner. 1896. 114 pp.

B 164. Reconnaissance on the Rio Grande coal fields of Texas, by T. W. Vaughan, including a report on igneous rocks from the San Carlos coal field, by E. C. E. Lord. 1900. 100 pp 11 pls. (Out of stock.)

B 178. El Paso tin deposits, by W. H. Weed. 1901. 15 pp., 1 pl.

B 180. Occurrence and distribution of corundum in United States, by J. H. Pratt. 1901. 98 pp., 14 pls. (Out of stock; see No. 269.)

B 182. A report on the economic geology of the Silverton quadrangle, Colorado, by F. L. Ransome. 1901. 266 pp., 16 pls. (Out of stock.)

B 184. Oil and gas fields of the western interior and northern Texas Coal Measures and of the Upper Cretaceous and Tertiary of the western Gulf coast, by G. I. Adams. 1901. 64 pp., 10 pls. (Out of stock.)

B 193. The geological relations and distribution of platinum and associated metals, by J. F. Kemp. 1902. 95 pp., 6 pls.

B 198. The Berea grit oil sand in the Cadiz quadrangle, Ohio, by W. T. Griswold. 1902. 43 pp., 1 pl. (Out of stock.)

PP 1. Preliminary report on the Ketchikan mining district, Alaska, with an introductory sketch of the geology of southeastern Alaska, by A. H. Brooks. 1902. 120 pp., 2 pls.

B 200. Reconnaissance of the borax deposits of Death Valley and Mohave Desert, by M. R. Campbell. 1902. 23 pp., 1 pl. (Out of stock.)

B 202. Tests for gold and silver in shales from western Kansas, by Waldemar Lindgren. 1902. 21 pp. (Out of stock.)

PP 2. Reconnaissance of the northwestern portion of Seward Peninsula, Alaska, by A. J. Collier. 1902. 70 pp., 11 pls.

PP 10. Reconnaissance from Fort Hamlin to Kotzebue Sound, Alaska, by way of Dall, Kanuti, Allen, and Kowak rivers, by W. C. Mendenhall. 1902. 68 pp., 10 pls.

PP 11. Clays of the United States east of the Mississippi River, by Heinrich Ries. 1903. 298 pp., 9 pls. (Out of stock.)

PP 12. Geology of the Globe copper district, Arizona, by F. L. Ransome. 1903. 168 pp., 27 pls.

B 212. Oil fields of the Texas-Louisiana Gulf Coastal Plain, by C. W. Hayes and William Kennedy. 1903. 174 pp., 11 pls. (Out of stock.)

B 213. Contributions to economic geology, 1902; S. F. Emmons and C. W. Hayes, geologists in charge. 1903. 449 pp. (Out of stock.)

PP 15. The mineral resources of the Mount Wrangell district, Alaska, by W. C. Mendenhall and F. C. Schrader. 1903. 71 pp., 10 pls.

B 218. Coal resources of the Yukon, Alaska, by A. J. Collier. 1903. 71 pp., 6 pls.

B 219. The ore deposits of Tonopah, Nevada (preliminary report), by J. E. Spurr. 1903. 31 pp., 1 pl. (Out of stock.)

PP 20. A reconnaissance in northern Alaska in 1901, by F. C. Schrader. 1904. 139 pp., 16 pls.

PP 21. Geology and ore deposits of the Bisbee quadrangle, Arizona, by F. L. Ransome. 1904. 168 pp. 29 pls.

B 223. Gypsum deposits in the United States, by G. I. Adams and others. 1904. 129 pp., 21 pls. (Out of stock.)

PP 24. Zinc and lead deposits of northern Arkansas, by G. I. Adams. 1904. 118 pp., 27 pls.

PP 25. Copper deposits of the Encampment district, Wyoming, by A. C. Spencer. 1904. 107 pp., 2 pls. (Out of stock.)

B 225. Contributions to economic geology, 1903, by S. F. Emmons and C. W. Hayes, geologists in charge. 1904. 527 pp., 1 pl. (Out of stock.)

PP 26. Economic resources of the northern Black Hills, by J. D. Irving, with contributions by S. F. Emmons and T. A. Jaggar, jr. 1904. 222 pp., 20 pls.

PP 27. A geological reconnaissance across the Bitterroot Range and Clearwater Mountains in Montana and Idaho, by Waldemar Lindgren. 1904. 123 pp., 15 pls.

B 229. Tin deposits of the York region, Alaska, by A. J. Collier. 1904. 61 pp., 7 pls.

B 236. The Porcupine placer district, Alaska, by C. W. Wright. 1904. 35 pp., 10 pls.

B 238. Economic geology of the Iola quadrangle, Kansas, by G. I. Adams, Erasmus Haworth, and W. R. Crane. 1904. 83 pp., 11 pls.

B 243. Cement materials and industry of the United States, by E. C. Eckel. 1905. 395 pp., 15 pls.

B 246. Zinc and lead deposits of northwestern Illinois, by H. Foster Bain. 1904. 56 pp., 5 pls.

B 247. The Fairhaven gold placers of Seward Peninsula, Alaska, by F. H. Moffit. 1905. 85 pp., 14 pls.

B 249. Limestones of southeastern Pennsylvania, by F. G. Clapp. 1905. 52 pp., 7 pls.

B 250. The petroleum fields of the Pacific coast of Alaska, with an account of the Bering River coal deposits, by G. C. Martin. 1905. 65 pp., 7 pls.

B 251. The gold placers of the Fortymile, Birch Creek, and Fairbanks regions, Alaska, by L. M. Prindle. 1905. 89 pp., 16 pls.

WS 117. The lignite of North Dakota and its relation to irrigation, by F. A. Wilder. 1905. 59 pp., 8 pls.

PP 36. The lead, zinc, and fluorspar deposits of western Kentucky, by E. O. Ulrich and W. S. T. Smith. 1905. 218 pp., 15 pls.

PP 38. Economic geology of the Bingham mining district, Utah, by J. M. Boutwell, with a chapter on areal geology, by Arthur Keith, and an introduction on general geology, by S. F. Emmons. 1905. 413 pp., 49 pls.

PP 41. Geology of the central Copper River region, Alaska, by W. C. Mendenhall. 1905. 133 pp., 20 pls.

B 254. Report of progress in the geological resurvey of the Cripple Creek district, Colorado, by Waldemar Lindgren and F. L. Ransome. 1904. 36 pp.

B 255. The fluorspar deposits of southern Illinois, by H. Foster Bain. 1905. 75 pp., 6 pls. (Out of stock.)

B 256. Mineral resources of the Elders Ridge quadrangle, Pennsylvania, by R. W. Stone. 1905. 86 pp., 12 pls.

B 259. Report on progress of investigations of mineral resources of Alaska in 1904, by A. H. Brooks and others. 1905. 196 pp., 3 pls.

B 260. Contributions to economic geology, 1904; S. F. Emmons and C. W. Hayes, geologists in charge. 1905. 620 pp., 4 pls.

B 261. Preliminary report on the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, and M. R. Campbell, committee in charge. 1905. 172 pp. (Out of stock.)

B 263. Methods and cost of gravel and placer mining in Alaska, by C. W. Purington. 1905. 273 pp., 42 pls. (Out of stock.)

PP 42. Geology of the Tonopah mining district, Nevada, by J. E. Spurr. 1905. 295 pp., 24 pls.

PP 43. The copper deposits of the Clifton-Morenci district, Arizona, by Waldemar Lindgren. 1905. 375 pp., 25 pls.

B 264. Record of deep-well drilling for 1904, by M. L. Fuller, E. F. Lines, and A. C. Veatch. 1905. 106 pp.

B 265. Geology of the Boulder district, Colorado, by N. M. Fenneman. 1905. 101 pp., 5 pls.

B 267. The copper deposits of Missouri, by H. Foster Bain and E. O. Ulrich. 1905. 52 pp., 1 pl.

B 269. Corundum and its occurrence and distribution in the United States (a revised and enlarged edition of Bulletin No. 180), by J. H. Pratt. 1906. 175 pp., 18 pls.

PP 48. Report on the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1906. (In 3 parts.) 1,492 pp., 13 pls.

B 275. Slate deposits and slate industry of the United States, by T. N. Dale, with sections by E. C. Eckel, W. F. Hillebrand, and A. T. Coons. 1906. 154 pp., 25 pls.

PP 49. Geology and mineral resources of part of the Cumberland Gap coal field, Kentucky, by G. H. Ashley and L. C. Glenn, in cooperation with the State Geological Department of Kentucky, C. J. Norwood, curator. 1906. 239 pp., 40 pls.

B 277. Mineral resources of Kenai Peninsula, Alaska: Gold fields of the Turnagain Arm region, by F. H. Moffit; Coal fields of the Kachemak Bay region, by R. W. Stone. 1906. 80 pp., 18 pls.

B 278. Geology and coal resources of the Cape Lisburne region, Alaska, by A. J. Collier. 1906. 54 pp., 9 pls. (Out of stock.)

B 279. Mineral resources of the Kittanning and Rural Valley quadrangles, Pennsylvania, by Charles Butts. 1906. 198 pp., 11 pls.

B 280. The Rampart gold placer region, Alaska, by L. M. Prindle and F. L. Hess. 1906. 54 pp., 7 pls. (Out of stock.)

B 282. Oil fields of the Texas-Louisiana Gulf Coastal Plain, by N. M. Fenneman. 1906. 146 pp., 11 pls.

PP 51. Geology of the Bighorn Mountains, by N. H. Darton. 1906. 129 pp., 47 pls.

B 283. Geology and mineral resources of Mississippi, by A. F. Crider. 1906. 99 pp., 4 pls.

B 284. Report on progress of investigations of the mineral resources of Alaska in 1905, by A. H. Brook and others. 1906. 169 pp., 14 pls.

B 285. Contributions to Economic Geology, 1905; S. F. Emmons and E. C. Eckel, geologists in charge. 1906. 506 pp., 13 pls. (Out of stock.)

B 286. Economic geology of the Beaver quadrangle, Pennsylvania, by L. H. Woolsey. 1906. 132 pp., 8 pls.

B 287. Juneau gold belt, Alaska, by A. C. Spencer, and A reconnaissance of Admiralty Island, Alaska, by C. W. Wright. 1906. 161 pp., 27 pls.

PP 54. The geology and gold deposits of the Cripple Creek district, Colorado, by W. Lindgren and F. L. Ransome. 1906. 516 pp., 29 pls.

PP 55. Ore deposits of the Silver Peak quadrangle, Nevada, by J. E. Spurr. 1906. 174 pp., 24 pls.

B 289. A reconnaissance of the Matanuska coal field, Alaska, in 1905, by G. C. Martin. 1906. 34 pp., 5 pls.

B 290. Preliminary report on the operations of the fuel-testing plant of the United States Geological Survey at St. Louis, Mo., 1905, by J. A. Holmes. 1906. 240 pp.

B 293. Reconnaissance of some gold and tin deposits of the southern Appalachians, by L. C. Graton, with notes on the Dahlonega mines, by W. Lindgren. 1906. 134 pp., 9 pls.

B 294. Zinc and lead deposits of the upper Mississippi Valley, by H. Foster Bain. 1906. 155 pp., 16 pls.

B 295. The Yukon-Tanana region, Alaska, description of Circle quadrangle, by L. M. Prindle. 1906. 27 pp., 1 pl.

B 296. Economic geology of the Independence quadrangle, Kansas, by Frank C. Schrader and Erasmus Haworth. 1906. 74 pp., 6 pls.

B 297. The Yampa coal field, Routt County, Colo., by N. M. Fenneman, Hoyt S. Gale, and M. R. Campbell. 1906. 96 pp., 9 pls.

B 298. Record of deep-well drilling for 1905, by Myron L. Fuller and Samuel Sanford. 1906. 299 pp.

B 300. Economic geology of the Amity quadrangle in eastern Washington County, Pa., by Frederick G. Clapp. 1907. 145 pp., 8 pls.

B 303. Preliminary account of Goldfield, Bullfrog, and other mining districts in southern Nevada, by F. L. Ransome, with notes on the Manhattan district, by G. H. Garrey and W. H. Emmons. 1906. 98 pp., 5 pls.

B 304. Oil and gas fields of Greene County, Pa., by Ralph W. Stone and Frederick G. Clapp. 1906. 110 pp., 3 pls.

PP 56. Geography and geology of a portion of southwestern Wyoming, with special reference to coal and oil, by A. C. Veatch. 1907. 178 pp., 26 pls.

B 308. A geologic reconnaissance in southwestern Nevada and eastern California, by S. H. Ball. 1907. 218 pp., 3 pls.

B 309. The Santa Clara Valley, Puente Hills, and Los Angeles oil districts, southern California, by G. H. Eldridge and Ralph Arnold. 1907. 266 pp., 41 pls.

B 312. The interaction between minerals and water solutions, with special reference to geologic phenomena, by E. C. Sullivan. 1907. 69 pp.

B 313. The granites of Maine, by T. Nelson Dale, with an introduction by G. O. Smith. 1907. 202 pp., 14 pls.

B 314. Report of progress of investigations of mineral resources of Alaska in 1906, by A. H. Brooks and others. 1907. 235 pp., 4 pls.

B 315. Contributions to economic geology, 1906, Part I: Metals and nonmetals, except fuels. S. F. Emmons and E. C. Eckel, geologists in charge. 1907. 504 pp., 4 pls.

WS 215. Geology and water resources of a portion of the Missouri River Valley in northeastern Nebraska, by G. E. Condra. 1908. — pp., 11 pls.

WS 216. Geology and water resources of the Republican River Valley in Nebraska and adjacent areas, by G. E. Condra. 1907. 71 pp., 13 pls.

B 316. Contributions to economic geology, 1906, Part II: Coal, lignite, and peat. M. R. Campbell, geologist in charge. 1907. 543 pp., 23 pls.

B 317. Preliminary report on the Santa Maria oil district, Santa Barbara County, Cal., by Ralph Arnold and Robert Anderson. 1907. 69 pp., 2 pls.

B 318. Geology of oil and gas fields in Steubenville, Burgettstown, and Claysville quadrangles, Ohio, West Virginia, and Pennsylvania, by W. T. Griswold and M. J. Munn. 1907. 196 pp., 13 pls.

B 320. The Downtown district of Leadville, Colo., by S. F. Emmons and J. D. Irving. 1907. 75 pp., 7 pls.

B 321. Geology and oil resources of the Summerland district, Santa Barbara County, Cal., by Ralph Arnold. 1907. 91 pp., 20 pls.

B 322. Geology and oil resources of the Santa Maria oil district, Santa Barbara County, Cal., by Ralph Arnold and Robert Anderson. 161 pp., 26 pls.

B 326. The Arkansas coal field, by A. J. Collier, with reports on the paleontology, by David White and G. H. Girty. 1907. 158 pp., 6 pls.

SERIES B, DESCRIPTIVE GEOLOGY.

B 23. Observations on the junction between the Eastern sandstone and the Keweenaw series on Keweenaw Point, Lake Superior, by R. D. Irving and T. C. Chamberlin. 1885. 124 pp., 17 pls. (Out of stock.)

B 33. Notes on geology of northern California, by J. S. Diller. 1886. 23 pp. (Out of stock.)

B 39. The upper beaches and deltas of Glacial Lake Agassiz, by Warren Upham. 1887. 84 pp., 1 pl. (Out of stock.)

B 40. Changes in river courses in Washington Territory due to glaciation, by Bailey Willis. 1887. 10 pp., 4 pls. (Out of stock.)

B 45. The present condition of knowledge of the geology of Texas, by R. T. Hill. 1887. 94 pp. (Out of stock.)

B 53. The geology of Nantucket, by N. S. Shaler. 1889. 55 pp., 10 pls. (Out of stock.)

B 57. A geological reconnaissance in southwestern Kansas, by Robert Hay. 1890. 49 pp., 2 pls.

B 58. The glacial boundary in western Pennsylvania, Ohio, Kentucky, Indiana, and Illinois, by G. F. Wright, with introduction by T. C. Chamberlin. 1890. 112 pp., 8 pls. (Out of stock.)

B 67. The relations of the traps of the Newark system in the New Jersey region, by N. H. Darton. 1890. 82 pp. (Out of stock.)

B 104. Glaciation of the Yellowstone Valley north of the Park, by W. H. Weed. 1893. 41 pp., 4 pls.

B. 108. A geological reconnaissance in central Washington, by I. C. Russell. 1893. 108 pp., 12 pls. (Out of stock.)

B 119. A geological reconnaissance in northwest Wyoming, by G. H. Eldridge. 1894. 72 pp., 4 pls.

B 137. The geology of the Fort Riley Military Reservation and vicinity, Kansas, by Robert Hay. 1896. 35 pp., 8 pls.

B 144. The moraines of the Missouri Coteau and their attendant deposits, by J. E. Todd. 1896. 71 pp., 21 pls.

B 158. The moraines of southeastern South Dakota and their attendant deposits, by J. E. Todd. 1899. 171 pp., 27 pls.

B 159. The geology of eastern Berkshire County, Massachusetts, by B. K. Emerson. 1899. 139 pp., 9 pls.

B 165. Contributions to the geology of Maine, by H. S. Williams and H. E. Gregory. 1900. 212 pp., 14 pls.

WS 70. Geology and water resources of the Patrick and Goshen Hole quadrangles in eastern Wyoming and western Nebraska, by G. I. Adams. 1902. 50 pp., 11 pls.

B 199. Geology and water resources of the Snake River Plains of Idaho, by I. C. Russell. 1902. 192 pp., 25 pls.

PP 1. Preliminary report on the Ketchikan mining district, Alaska, with an introductory sketch of the geology of southeastern Alaska, by A. H. Brooks. 1902. 120 pp., 2 pls.

PP 2. Reconnaissance of the northwestern portion of Seward Peninsula, Alaska, by A. J. Collier. 1902. 70 pp., 11 pls.

PP 3. Geology and petrography of Crater Lake National Park, by J. S. Diller and H. B. Patton. 1902. 167 pp., 19 pls.

PP 10. Reconnaissance from Fort Hamlin to Kotzebue Sound, Alaska, by way of Dall, Kanuti, Allen, and Kowak rivers, by W. C. Mendenhall. 1902. 68 pp., 10 pls.

PP 11. Clays of the United States east of the Mississippi River, by Heinrich Ries. 1903. 298 pp., 9 pls. (Out of stock.)

PP 12. Geology of the Globe copper district, Arizona, by F. L. Ransome. 1903. 168 pp., 27 pls.

PP 13. Drainage modifications in southeastern Ohio and adjacent parts of West Virginia and Kentucky, by W. G. Tight. 1903. 111 pp., 17 pls. (Out of stock.)

B 208. Descriptive geology of Nevada south of the fortieth parallel and adjacent portions of California, by J. E. Spurr. 1903. 229 pp., 8 pls. (Out of stock.)

B 209. Geology of Ascutney Mountain, Vermont, by R. A. Daly. 1903. 122 pp., 7 pls.

WS 78. Preliminary report on artesian basins in southwestern Idaho and southeastern Oregon, by I. C. Russell. 1903. 51 pp., 2 pls.

PP 15. Mineral resources of the Mount Wrangell district, Alaska, by W. C. Mendenhall and F. C. Schrader. 1903. 71 pp., 10 pls.

PP 17. Preliminary report on the geology and water resources of Nebraska west of the one hundred and third meridian, by N. H. Darton. 1903. 69 pp., 43 pls.

B 217. Notes on the geology of southwestern Idaho and southeastern Oregon, by I. C. Russell. 1903. 83 pp., 18 pls.

B 219. The ore deposits of Tonopah, Nevada (preliminary report), by J. E. Spurr. 1903. 31 pp., 1 pl.

PP 20. A reconnaissance in northern Alaska in 1901, by F. C. Schrader. 1904. 139 pp., 16 pls.

PP 21. The geology and ore deposits of the Bisbee quadrangle, Arizona, by F. L. Ransome. 1904. 168 pp., 29 pls.

WS 90. Geology and water resources of part of the lower James River Valley, South Dakota, by J. E. Todd and C. M. Hall. 1904. 47 pp., 23 pls.

PP 25. The copper deposts of the Encampment district, Wyoming, by A. C. Spencer. 1904. 107 pp. 2 pls. (Out of stock.)

PP 26. Economic resources of the northern Black Hills, by J. D. Irving, with contributions by S. F. Emmons and T. A. Jaggar, jr. 1904. 222 pp., 20 pls.

PP 27. A geological reconnaissance across the Bitterroot Range and Clearwater Mountains in Montana and Idaho, by Waldemar Lindgren. 1904. 122 pp., 15 pls.

PP 31. Preliminary report on the geology of the Arbuckle and Wichita mountains in Indian Territory and Oklahoma, by J. A. Taff, with an appendix on reported ore deposits in the Wichita Mountains, by H. F. Bain. 1904. 97 pp., 8 pls.

B 235. A geological reconnaissance across the Cascade Range near the forty-ninth parallel, by G. O. Smith and F. C. Calkins. 1904. 103 pp., 4 pls.

B 236. The Porcupine placer district, Alaska, by C. W. Wright. 1904. 35 pp., 10 pls.

B 237. Igneous rocks of the Highwood Mountains, Montana, by L. V. Pirsson. 1904. 208 pp., 7 pls.

B 238. Economic geology of the Iola quadrangle, Kansas, by G. I. Adams, Erasmus Haworth, and W. R. Crane. 1904. 83 pp., 1 pl.

PP 32. Geology and underground water resources of the central Great Plains, by N. H. Darton. 1905. 433 pp., 72 pls.

WS 110. Contributions to hydrology of eastern United States, 1904. M. L. Fuller, geologist in charge. 1905. 211 pp., 5 pls.

B 242. Geology of the Hudson Valley between the Hoosic and the Kinderhook, by T. Nelson Dale. 1904. 63 pp., 3 pls.

PP 34. The Delavan lobe of the Lake Michigan glacier of the Wisconsin stage of glaciation and associated phenomena, by W. C. Alden. 1904. 106 pp., 15 pls.

PP 35. Geology of the Perry Basin in southeastern Maine, by G. O. Smith and David White. 1905. 107 pp., 6 pls.

B 243. Cement materials and industry of the United States, by E. C. Eckel. 1905. 395 pp., 15 pls.

B 246. Zinc and lead deposits of northeastern Illinois, by H. F. Bain. 1904. 56 pp., 5 pls.

B 247. The Fairhaven gold placers of Seward Peninsula, Alaska, by F. H. Moffit. 1905. 85 pp., 14 pls.

B 249. Limestones of southwestern Pennsylvania, by F. G. Clapp. 1905. 52 pp., 7 pls.

B 250. The petroleum fields of the Pacific coast of Alaska, with an account of the Bering River coal deposit, by G. C. Martin. 1905. 65 pp., 7 pls.

B 251. The gold placers of the Fortymile, Birch Creek, and Fairbanks regions, Alaska, by L. M. Prindle. 1905. 16 pp., 16 pls.

WS 118. Geology and water resources of a portion of east-central Washington, by F. C. Calkins. 1905. 96 pp., 4 pls.

B 252. Preliminary report on the geology and water resources of central Oregon, by I. C. Russell. 1905. 138 pp., 24 pls.

PP 36. The lead, zinc, and fluorspar deposits of western Kentucky, by E. O. Ulrich and W. S. Tangier Smith. 1905. 218 pp., 15 pls.

PP 38. Economic geology of the Bingham mining district of Utah, by J. M. Boutwell, with a chapter on areal geology, by Arthur Keith, and an introduction on general geology, by S. F. Emmons. 1905. 413 pp., 49 pls.

PP 41. The geology of the central Copper River region, Alaska, by W. C. Mendenhall. 1905. 133 pp., 20 pls.

B 254. Report of progress in the geological resurvey of the Cripple Creek district, Colorado, by Waldemar Lindgren and F. L. Ransome. 1904. 36 pp.

B 255. The fluorspar deposits of southern Illinois, by H. Foster Bain. 1905. 75 pp., 6 pls. (Out of stock.)

B 256. Mineral resources of the Elders Ridge quadrangle, Pennsylvania, by R. W. Stone. 1905. 85 pp., 12 pls.

B 257. Geology and paleontology of the Judith River beds, by T. W. Stanton and J. B. Hatcher, with a chapter on the fossil plants, by F. H. Knowlton. 1905. 174 pp., 19 pls.

PP 42. Geology of the Tonopah mining district, Nevada, by J. E. Spurr. 1905. 295 pp., 24 pls.

WS 123. Geology and underground water conditions of the Jornada del Muerto, New Mexico, by C. R. Keyes. 1905. 42 pp., 9 pls. (Out of stock.)

WS 136. Underground waters of Salt River Valley, Arizona, by W. T. Lee. 1905. 194 pp., 24 pls.

PP. 43. The copper deposits of Clifton-Morenci, Arizona, by Waldemar Lindgren. 1905. 375 pp., 25 pls.

B 265. Geology of the Boulder district, Colorado, by N. M. Fenneman. 1905. 101 pp., 5 pls.

B 267. The copper deposits of Missouri, by H. F. Bain and E. O. Ulrich. 1905. 52 pp., 1 pl.

PP 44. Underground water resources of Long Island, New York, by A. C. Veatch and others. 1905. 394 pp., 34 pls.

WS 148. Geology and water resources of Oklahoma, by C. N. Gould. 1905. 178 pp., 22 pls.

B 270. The configuration of the rock floor of Greater New York, by W. H. Hobbs. 1905. 96 pp., 5 pls.

B 272. Taconic physiography, by T. M. Dale. 1905. 52 pp., 14 pls.

PP 45. The geography and geology of Alaska, a summary of existing knowledge, by A. H. Brooks, with a section on climate, by Cleveland Abbe, jr., and a topographic map and description thereof, by R. M. Goode. 1905. 327 pp., 34 pls.

B 273. The drumlins of southeastern Wisconsin (preliminary paper), by W. C. Alden. 1905. 46 pp., 9 pls.

PP 46. Geology and underground water resources of northern Louisiana and southern Arkansas, by A. C. Veatch. 1906. 422 pp., 51 pls.

PP 49. geology and mineral resources of part of the Cumberland Gap coal field, Kentucky, by G. H. Ashley and L. C. Glenn, in cooperation with the State Geological Department of Kentucky. C. J. Norwood, curator. 1906. 239 pp.. 40 pls.

PP 50. The Montana lobe of the Keewatin ice sheet, by F. H. H. Calhoun. 1906. 62 pp., 7 pls.

B 277. Mineral resources of Kenai peninsula, Alaska: Gold fields of the Turnagain Arm region, by F. H. Moffit; and the coal fields of the Kachemak Bay region, by R. W. Stone. 1906. 80 pp., 18 pls.

WS 154. The geology and water resources of the eastern portion of the Panhandle of Texas, by C. N. Gould. 1906. 64 pp., 15 pls.

B 278. Geology and coal resources of the Cape Lisburne region, Alaska, by A. J. Collier. 1906. 54 pp., 9 pls. (Out of stock.)

B 279. Mineral resources of the Kittanning and Rural Valley quadrangles, Pennsylvania, by Charles Butts. 1906. 198 pp., 11 pls.

B 280. The Rampart gold placer region, Alaska, by L. M. Prindle and F. L. Hess. 1906. 54 pp., 7 pls. (Out of stock.)

B 282. Oil fields of the Texas-Louisiana Gulf Coastal Plain, by N. M. Fenneman. 1906. 146 pp., 11 pls.

WS 157. Underground water in the valleys of Utah Lake and Jordan River, Utah, by G. B. Richardson. 1906. 81 pp., 9 pls.

PP 51. Geology of the Bighorn Mountains, by N. H. Darton. 1906. 129 pp., 47 pls.

WS 158. Preliminary report on the geology and underground waters of the Roswell artesian area, New Mexico, by C. A. Fisher. 1906. 29 pp., 9 pls.

PP 52. Geology and underground waters of the Arkansas Valley in eastern Colorado, by N. H. Darton. 1906. 90 pp., 28 pls.

WS 159. Summary of underground-water resources of Mississippi, by A. F. Crider and L. C. Johnson. 1906. 86 pp., 6 pls.

PP 53. Geology and water resources of the Bighorn basin, Wyoming, by C. A. Fisher. 1906. 72 pp., 16 pls.

B 283. Geology and mineral resources of Mississippi, by A. F. Crider. 1906. 99 pp., 4 pls.

B 286. Economic geology of the Beaver quadrangle, Pennsylvania (southern Beaver and northwestern Allegheny counties), by L. H. Woolsey. 1906. 132 pp., 8 pls.

B 287. The Juneau gold belt, Alaska, by A. C. Spencer, and a reconnaissance of Admiralty Island, Alaska, by C. W. Wright. 1906. 161 pp., 37 pls.

PP 54. The geology and gold deposits of the Cripple Creek district, Colorado, by W. Lindgren and F. L. Ransome. 1906. 516 pp., 29 pls.

PP 55. Ore deposits of the Silver Peak quadrangle, Nevada, by J. E. Spurr. 1906. 174 pp., 24 pls.

B 289. A reconnaissance of the Matanuska coal field, Alaska, in 1905, by G. C. Martin. 1906. 36 pp. 5 pls.

WS 164. Underground waters of Tennessee and Kentucky west of Tennessee River and of an adjacent area in Illinois, by L. C. Glenn. 1906. 173 pp., 7 pls.

B 293. Reconnaissance of some gold and tin deposits of the southern Appalachians, by L. C. Groton, with notes on the Dahlonega mines, by W. Lindgren. 1906. 134 pp., 9 pls.

B 294. Zinc and lead deposits of the upper Mississippi Valley, by H. Foster Bain. 1906. 155 pp., 16 pls.

B 295. The Yukon-Tanana region, Alaska, description of Circle quadrangle, by L. M. Prindle. 1906. 27 pp., 1 pl.

B 296. Economic geology of the Independence quadrangle, Kansas, by Frank C. Schrader and Erasmus Haworth. 1906. 74 pp., 6 pls.

WS 181. Geology and water resources of Owens Valley, California, by Willis T. Lee. 1906. 28 pp., 6 pls.

B 297. The Yampa coal field, Routt County, Colo., by N. M. Fenneman, Hoyt S. Gale, and M. R. Campbell. 1906. 96 pp., 9 pls.

B 300. Economic geology of the Amity quadrangle in eastern Washington County, Pa., by F. G. Clapp. 1906. 145 pp., 8 pls.

B 303. Preliminary account of Goldfield, Bullfrog, and other mining districts in southern Nevada, by F. L. Ransome; with notes on Manhattan district, by G. H. Garrey and W. H. Emmons. 1907. 98 pp., 5 pls.

B 304. Oil and gas fields of Greene County, Pa., by R. W. Stone and F. G. Clapp. 1907. 110 pp., 3 pls.

WS 188. Water resources of the Rio Grande Valley in New Mexico and their development, by W. T. Lee. 1906. 59 pp., 10 pls.

B 306. Rate of recession of Niagara Falls, accompanied by a report on the survey of the crest, by W. Carvel Hall. 1906. 31 pp., 11 pls.

PP 56. Geography and geology of a portion of southwestern Wyoming, with special reference to coal and oil, by A. C. Veatch. 1907. 178 pp., 26 pls.

B 308. A geologic reconnaissance in southwestern Nevada and eastern California, by S. H. Ball. 1907. 218 pp., 3 pls.

B 309. The Santa Clara Valley, Puente Hills, and Los Angeles oil districts, southern California, by G. H. Eldridge and Ralph Arnold. 1907. 266 pp., 41 pls.

PP 57. Geology of the Marysville mining district, Montana, a study of igneous intrusion and contact metamorphism, by Joseph Barrell. 1907. 178 pp., 16 pls.

WS 191. The geology and water resources of the western portion of the Panhandle of Texas, by C. N. Gould. 1907. 70 pp., 7 pls.

B 311. The green schists and associated granites and porphyries of Rhode Island, by B. K. Emerson and J. H. Perry. 1907. 74 pp., 2 pls.

WS 195. Underground waters of Missouri, their geology and utilization, by Edward Shepard. 1907. 224 pp., 6 pls.

WS 199. Underground water in Sanpete and central Sevier valleys, Utah, by G. B. Richardson. 1907. 63 pp., 6 pls.

WS 215. Geology and water resources of a portion of the Missouri River Valley in northeastern Nebraska, by G. E. Condra. 1908. — pp., 11 pls.

WS 216. Geology and water resources of the Republican River Valley in Nebraska and adjacent areas, by G. E. Condra. 1907. 71 pp., 13 pls.

B 317. Preliminary report on the Santa Maria oil district, Santa Barbara County, Cal., by Ralph Arnold and Robert Anderson. 1907. 69 pp., 2 pls.

B 318. Geology of oil and gas fields in Steubenville, Burgettstown, and Claysville quadrangles, Ohio, West Virginia, and Pennsylvania, by W. T. Griswold and M. J. Munn. 1907. 196 pp., 13 pls.

B 319. Summary of controlling factors of artesian flows, by M. L. Fuller. 1908. — pp., 7 pls.

B 320. The Downtown district of Leadville, Colo., by S. F. Emmons and J. D. Irving. 1907. 75 pp., 7 pls.

B 321. Geology and oil resources of the Summerland district, Santa Barbara County, Cal., by Ralph Arnold. 1907. 91 pp., 20 pls.

B 822. Geology and oil resources of the Santa Maria oil district, Santa Barbara County, Cal., by Ralph Arnold and Robert Anderson. 1907. 161 pp., 26 pls.

B 826. The Arkansas coal field, by A. J. Collier, with reports on the paleontology, by David White and G. H. Girty. 1907. 158 pp., 6 pls.

Correspondence should be addressed to

THE DIRECTOR,
UNITED STATES GEOLOGICAL SURVEY,
WASHINGTON, D. C.

DECEMBER, 1907.

O

Stanford University Libraries

3 6105 019 731 749

Stanford University Library
Stanford, California

In order that others may use this book, please return it as soon as possible, but not later than the date due.